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GROUNDWATER ISSUES: AN OVERVIEW

by

J.A. Vonhof

Vonhof Consulting Limited
Calgary

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THE INQUIRY ON FEDERAL WATER POLICY

The Inquiry on Federal Water Policy was appointed by the federal Minister of the Environment in January of 1984 under the authority of the Canada Water Act. The members were Peter H. Pearse, chairman; Françoise Bertrand, member; and James W. MacLaren, member. The Inquiry was required by its terms of reference to review matters of water policy and management within federal jurisdiction and to make recommendations.

This document is one of a series of research papers commissioned by the Inquiry to advance its investigation. The views and conclusions expressed in the research papers are those of the authors. Copies of research papers and information on the series may be obtained by writing to the Enquiry Centre, Environment Canada, Ottawa, Ontario K1A 0H3.

Frank Quinn
Director of Research

Abstract

Groundwater is a neglected resource in Canada. Although approximately 30 percent of the population depends on groundwater, the diffuse distribution of users, primarily the rural population, has resulted in relatively little attention on groundwater development and protection by government agencies.

Although it has long been recognized that surface water and groundwater are components of an interactive system, the effects of surface water development on groundwater flow systems is generally neglected, as is the effect of induced changes in groundwater systems on downstream users of the total water resource.

The attention paid by the province to the protection of groundwater resources is a function of their relevance as a source of potable water. Because of the inevitable time delay between the introduction of a contaminant into a groundwater flow system and its re-entry into another part of the terrestrial environment, groundwater contamination is generally not regarded as a politically urgent problem.

Groundwater contamination problems in various parts of the country are in many instances unique and determined by the industrial activity and resource base. It is not possible at this time to accurately assess the extent and severity of groundwater contamination because there is no readily available data base.

In order to protect groundwater resources, and indirectly the quality of surface water resources, for the future, it is suggested that the federal government assume a much more active role. The protection of this resource is in the national interest and should as such be defined in a federal policy. The protection strategy developed by the Environmental Protection Agency in the United States could serve as a model for policy planning by the Canadian government.

Résumé

Les eaux souterraines sont une ressource négligée au Canada. Bien qu'environ 30% de la population utilise les eaux souterraines, la dispersion de ces utilisateurs, majoritairement des utilisateurs ruraux, explique le fait que peu d'attention ait été accordé à la protection et au développement de cette ressource.

Bien qu'il soit depuis longtemps reconnu que les eaux de surface et souterraines sont des composantes d'un même système, les effects du développement des eaux de surface sur l'écoulement des eaux souterraines sont généralement négligés; il en est de même des effets provoqués par un changement dans le réseau des eaux souterraines sur les utilisateurs de la ressource eau en aval de ces changements.

L'attention apportée par les provinces à la protection des eaux souterraines est fonction de leur utilisation comme source d'eau potable. Parce qu'il y a

un délai inévitable entre l'introduction d'un contaminant dans les eaux souterraines et sa réapparition ailleurs dans l'environnement terrestre, la contamination des eaux souterraines n'est généralement pas reconnue comme un problème politique urgent.

Les problèmes de contamination des eaux souterraines sont souvent uniques à chacune des régions du pays et déterminés par l'activité industrielle et les ressources présentes. Il n'est pas possible actuellement d'évaluer de façon précise l'étendue et la sévérité de la contamination des eaux souterraines parce qu'il n'y a pas de base de donnée facilement accessible.

Afin de protéger les ressources en eaux souterraines et indirectement la qualité des eaux de surface, il est suggéré que le gouvernmement fédéral assume un rôle beaucoup plus actif. La protection de cette ressource est d'intérêt national et devrait donc être l'object d'une politique fédérale en la matière. La stratégie de protection développée par l'Agence de protection de l'environnement (EPA) des États-Unis pourrait servir de modèle de planification pour le gouvernement fédéral.

Groundwater Issues: An Overview

Objective

To assess the quantitative and qualitative stresses on Canadian groundwaters, and opportunities for greater conjunctive management with surfaace waters.

Tasks

1. Describe briefly groundwater properties and behaviour within the hydrologic cycle (introductory);

2. Assess problems of groundwater overdraft and their consequences (e.g. subsidence, salt-water intrusion, reduced contribution to streamflow); and opportunities for alleviating water shortages by induced recharge of aquifers and conjunctive use;

3. Assess the severity of groundwater contamination from various industrial, municipal and agricultural sources, and progress in controlling these sources; consider the long term effects of waste disposal practices;

4. Recommend measures by which the federal government can contribute appropriately to improved groundwater management, through data, research and/or other interjurisdictional programs.

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I. GROUNDWATER AND THE HYDROLOGIC CYCLE

1.1 Introduction

It is estimated that the earth contains approximately 1.36×10^9 km^3 of water, 97.5 percent or 1.33×10^9 km^3 of which is salt water. Of the remaining 2.5 percent, which makes up the world's total freshwater supply, 87.3 percent or 3.33×10^7 km^3 is frozen in the polar ice caps and in glaciers in various parts of the world, 12.3 percent or 4.1×10^6 km^3 is groundwater and of the final 0.4 percent or 1.34×10^5 km^3 some is stored in lakes and rivers and some is present in the atmosphere (Morris, 1969). Figure 1 summarizes the distribution of the water resources of the earth. It is obvious from figure 1 that groundwater constitutes the largest accessible source of freshwater.

The world's freshwater supply is maintained by a gigantic natural distillation and circulation system, i.e. the hydrologic cycle. Water evaporates from the earth's surface (oceans and land), condenses to form clouds, and is returned to the earth as precipitation (Fig. 2). The moisture which falls over land as precipitation may follow a number of different paths before it is returned to the atmosphere. Part of the precipitation evaporates while falling. Some of the precipitation that reaches the land surface quickly returns to the atmosphere through evaporation. A portion of the precipitation will result in runoff, which collects in streams or rivers and is subsequently transported toward lakes, seas and oceans. During its travel part of it will evaporate and the portion that reaches the final

destination will eventually be returned to the atmosphere by evaporation. Another part of precipitation will infiltrate into the ground. Upon infiltration it replaces the soil-moisture deficiency. Part of this water is lost to the atmosphere by upward capillary transport and subsequent evaporation, whereas another part is taken up by vegetation and a portion of this water is released to the atmosphere by transpiration. If the soil reaches a specific degree of saturation, infiltrating precipitation can reach the watertable, where it becomes part of the groundwater flow system.

Although the hydrologic cycle is simple in concept, the analysis of its components is an extremely complicated task due to the many alternative routes water may follow in every phase of the cycle and the different climatic, geological, and biological environments through which it moves. In this paper only one portion of the hydrologic cycle will be discussed, namely groundwater flow and the related topic of groundwater pollution. It is not the objective of this paper to discuss in detail the theory of groundwater flow or the chemical evolution of groundwater. Only those aspects which are considered relevant to the discussion are touched upon. For a complete review of groundwater flow the reader is referred to Freeze and Cherry (1979).

1.2 Groundwater Flow

In order to understand the occurrence and movement of groundwater and consequently the movement of pollutants, it is necessary to describe a few fundamentals of groundwater flow.

According to Hubbert (1940), groundwater flow takes place from regions with high fluid potential to regions with lower fluid potential, regardless of the direction of flow in space. The fluid potential is equal to the mechanical energy per unit mass of fluid. For flow through a porous medium where the flow velocities are extremely low and the liquid is isotropic and incompressible, it can be shown that the fluid potential is equal to the hydraulic head multiplied by the acceleration due to gravity. Since acceleration due to gravity is very nearly constant in the vicinity of the earth's surface, and certainly within finite study areas, the fluid potential is proportional to the hydraulic head. It can further be shown that the hydraulic head at a point in a groundwater flow system, if the reference datum used is mean sea level, is the elevation of the free water surface in a piezometer completed at that point. If the hydraulic head distribution of an area is considered under idealized conditions, i.e. homogeneous and isotropic, then the areas with higher fluid potential correspond to the topographically high regions, and areas with lower fluid potential occur in the topographically low regions. This is illustrated in Figure 3. By definition, that portion of the topographically high area in which the net saturated flow is directed downward, away from the watertable, is called a recharge area, whereas in a discharge area the net saturated flow is directed upward, toward the watertable. The effect of topography on the groundwater flow system has been discussed at length by Tóth (1963) and by Freeze and Witherspoon (1967). Both authors show that topography alone can create complex systems of groundwater flow.

Thus far groundwater flow patterns have been discussed in terms of idealized

environments, i.e. uniform permeability distribution. However, the permeability distribution of the natural environment is anything but uniform and is characterized by considerable variation in both a vertical and a lateral sense. Since the magnitude of the permeability of sediments is inherent to the type of sediment, and the distribution of a particular sediment is determined by the depositional environment, a first approximation of the permeability distribution in space can be obtained from a proper definition of the geological environment in the subsurface.

The main effect of variations in permeability is the bending of flow lines in such a way that the fluid mass is conserved when water flows across a boundary between strata of different permeability (Hubbert, 1940).

Figure 4 (after Freeze and Whitherspoon, 1967), shows a number of numerically simulated two-dimensional flow nets for heterogeneous geological systems, Figures 4 (a) and (b) show the fluid potential distribution in the subsurface with a highly permeable layer (aquifer) underlying a low permeability sediment (aquitard), but with different configurations of surface topography. A comparison between Figures 4 (a) and 4 (b) shows that in a similar geological setting topography greatly complicates the groundwater flow pattern. Furthermore, a highly permeable layer at depth acts as a major conduit for flow that passes under overlying local systems.

Figures 4 (c) and (d) show the effect of high permeability discontinuities on the groundwater flow pattern. In both instances, upward flow occurs near the downslope part of the high permeability discontinuity. Such middle slope discharge areas at surface cannot occur under purely topographic control.

Figures 4 (e) and (f) show the effect of sloping stratigraphy on the groundwater flow pattern. As can be seen in these figures, the direction of the slope of the highly permeable bed with respect to the recharge, or topographically high, area strongly affects the potential distribution within the subsurface.

The foregoing examples show that geological heterogeneity and topography have a pronounced effect on local and regional groundwater flow systems. Furthermore, it becomes apparent that, in order to be able to describe a groundwater flow system in any given area, knowledge of the distribution of the permeability in space is mandatory.

Permeability, as has been shown in the previous paragraphs, is one of the controlling factors in groundwater flow. Different types of permeability can be recognized. They are related to the mode of deposition, type of sediment and rock, post-depositional processes, and tectonic stresses. Figure 5 shows the different types of permeability and porosity. The significance of the different types of permeability will be shown below.

The rate of groundwater flow is a function of the available hydraulic head and the permeability distribution in an area. It varies from several tens of metres to a fraction of a centimetre per year. It is obvious from the foregoing that in any groundwater flow system the rate will be primarily controlled by the lowest permeability of the series of permeabilities encountered by the groundwater traveling from the recharge to the discharge area. Furthermore, the bulk of groundwater flow will be concentrated in the areas with the highest permeable paths, i.e. where the least amount of energy needs to be expended.

II. AQUIFERS

In the previous chapter the rudimentary principles of groundwater flow were explained. It should be pointed out that groundwater flow occurs in all sediments and rocks. The zone in the subsurface from which groundwater is obtained is called an aquifer.

An aquifer is any water-saturated body of geological material from which enough water can be drawn at a reasonable cost for the purpose required (Brown, 1967). An aquifer therefore is only a relative term, determined largely by economics and alternate sources. For example, in areas where water is scarce, a zone which can supply only enough water for daily domestic use (400-900 litres) is considered an aquifer. However, the same zone would not be considered an aquifer if multiples of the previously mentioned volume are required.

Three major types of aquifers are commonly recognized: unconfined, confined,and leaky (Fig. 6). Proper identification is important from a technical, managerial, and legal point of view because hydrologically they react in considerably different ways.

An unconfined or watertable aquifer has a free water surface, the water-table,exposed to the soil atmosphere. Water is released from the aquifer primarily by gravity drainage.

A confined, or artesian, aquifer is enclosed by layers of such low permeability that the water is confined to the intervening more permeable zone and under hydrostatic pressure in a manner similar to water in a tilted pipe. In other words, a well completed in a confined aquifer shows a static

water level at an elevation higher than the top of the aquifer. Withdrawal of water from a confined aquifer results in a lowering of the hydraulic head. Depending on the degree of the lowering of the hydraulic head in the pumping well the effect may be noticed over a wide area.

A leaky confined aquifer is closely related to a confined aquifer. It differs from a confined aquifer in that the "confining" beds have a sufficiently large vertical permeability that as a result of lowering of the hydraulic head in the aquifer water will move through the "confining" beds toward the aquifer. In other words, recharge to the aquifer takes place through the "confining" beds. Under similar conditions of initial head distribution, permeability, thickness, and pumping rate, the effect of the lowering of the hydraulic head due to pumping will not be as wide-spread in a leaky "confined" aquifer as in a confined aquifer. It should be pointed out that in the writer's opinion truly confined aquifers do not exist. The assignment of the label "leaky" is time dependent. Given sufficient time almost all confined aquifers will show a degree of leakage under stressed conditions.

In addition, certain characteristics unique to the geological environment in which the aquifer is found have a strong bearing on its character and permeability distribution, on recharge phenomena, and on its behaviour under stress, environmental sensitivity and productivity and, last but not least, on exploration strategy. Four main geological aquifer environments can be recognized.

Clastic sedimentary environment. The chief characteristic of sedimentary deposits is that they occur in comparatively thin sheets that may be of relatively great lateral extent. Most sediments in this environment are deposited in bodies of salt or fresh

water. Aeolian deposits, for example dunes, are an exception. The material comprising the sediment is transported mechanically, by water or wind, and is sorted with distance from its primary source. The ability to store and transmit water depends on the size, shape, and sorting of the constituent particles. Groundwater flow in this type of sediment in intergranular. Post-depositional changes, such as cementation, can significantly alter these parameters, as can subsequent tectonic events such as fracturing and faulting. However, not all sediments deposited in water are characterized by the above-mentioned degree of homogeneity. Fluvial sediments, and especially glacio-fluvial deposits, are noted for their rapid change in type of sediment and uniformity in both a lateral and a vertical sense. Understanding the local depositional environment, the sedimentation processes, and the geological history is therefore of paramount importance in the evaluation of the groundwater potential of a clastic sedimentary area.

Limestone and dolomite environment. The sediments in this environment, although belonging to the sedimentary environment in a geological sense, are discussed separately because of a number of processes which have a strong bearing on the flow of water. Limstone is formed by organisms which extract calcium carbonate from sea water. Penecontemporaneous erosion of the calcium carbonate deposits generally results in a highly complex sequence of calcareous deposits. Primary porosity, and permeability, are the result of the openings left by the organisms which originally built the carbonate rock. In the reworked carbonates the porosity is similar in origin to the porosity in clastic sediments. However, most limestones show considerable

secondary cementation and recrystallization, which has destroyed most of the primary porosity. Two processes which can drastically increase the porosity and permeability of limstones are dolomitization and karstification. Dolomitization is a diagenetic change during which calcium carbonate is replaced by magnesium-calcium carbonate (Morrow, 1982a). The origin of the majority of dolomites in the world is due to this process. Almost all models developed to explain this process require groundwater flow (fresh and/or saline) as the mechanism to introduce and supply the magnesium ions to the calcium carbonates (Morrow, 1982b). Dolomites in most instances are not a primary deposit but are formed penecontemporaneously or later due to diagenetic changes.

Dolomites can have a much higher permeability than limestones. According to Wardlaw (1979),this may be related to the idiomorphic shape and uniformity in size of the dolomite crystals. Intercrystalline porosity as high as 25 percent has been observed by the writer in several dolomites in Alberta.

Karstification is a process of leaching and decalcification of easily leachable rocks. It results in the formation of solution channels, cavity development, collapse structures, etc. Karstification dramatically increases the ability of limestones and dolomites to transmit groundwater. Very large volumes of water can be obtained from karstified limestones and dolomites. Many solution channels and cavities in karst areas are partially infilled with clastic material. During pumping this sediment can be removed, which results in an increase of the "permeability" (Weyer, 1983).

Crystalline (igneous and metamorphic) rock environment. The greater part of the surface of Canada is underlain by igneous and metamorphic rocks. They are the only potential aquifers in those areas where surficial sediments are thin or lacking. In contrast to the intergranular permeability of sedimentary rocks, crystalline rock environments exhibit primarily fracture permeability and porosity. The distribution of the primary macroscopic fracture permeability is a function of the tectonic and associated intrusive history, the degree of metamorphism, and the lithofacies in any given area. Although on a unit volume basis the permeability and porosity of crystalline rocks are small in comparison to those of unconsolidated sedimentary deposits, large volumes of water can be transmitted. Evidence of this is provided by the volumes of water pumped out of mines in this environment. Daily volumes range from 50,000 to 20,000,000 litres (Brown, 1967). For a more detailed and in-depth discussion of groundwater flow in fractured rock the reader is referred to Gale (1982).

Fractured sedimentary rocks. Fractured sedimentary rocks form a separate environment, which has characteristics of both the unconsolidated clastic sedimentary deposits and fractured crystalline rocks. The sediments in this environment have undergone considerable diagenetic change. Cementation of the coarser-grained facies is common and the sediments are generally consolidated. Intergranular porosity and permeability are generally considerably less than in their unconsolidated equivalents. However, due to tectonic stresses and deformation, extensive fracture patterns have developed in these environments, which greatly facilitate the movement of water.

It should be pointed out that fracturing of sedimentary deposits is

not restricted to those beds that are consolidated. Many tills (unconsolidated Pleistocene sediments) also show fracturing (Grisak et al., 1975; Vonhof, 1983). This aspect has considerable bearing on waste disposal practices in areas underlain by till. Furthermore, many clay-rich surficial unconsolidated sediments in Canada are subjected to drying cycles. This results in the development of a polygonal network of vertical desiccation cracks. Some of these cracks extend to depths of more than 10 metres. In many instances the cracks are infilled with organic matter and other sediment. The permeability of the infill material is generally orders of magnitude higher than that of the surrounding sediment. The desiccation cracks play a vital role in establishing and maintaining a moisture balance in the clay-rich sediments. The network of desiccation cracks, however, also provides relatively highly permeable pathways for contaminant transport in an otherwise very slightly permeable ("impermeable") environment.

The geological history of Canada determines the areal distribution of the main aquifer environments described above.

- The Cordilleran Region (primarily British Columbia and the Yukon) is characterized by crystalline and folded sedimentary rocks. However, because of population distribution, most groundwater is obtained from Pleistocene and Holocene sediment fill in valleys.
- The Interior Plains (Alberta, part of the Northwest Territories, southern Saskatchewan, and southwestern Manitoba) comprise essentially flat-lying unconsolidated and semi-consolidated sedimentary rocks. The majority of the groundwater is obtained from aquifers within the Pleistocene section.

- The Canadian Shield (northern Saskatchewan, the Northwest Territories, most of Manitoba, Ontario, Quebec, and Newfoundland) falls within the crystalline rock environment. In places glacial outwash, kames, and eskers are used as aquifers.
- The St. Laurence Lowland (southern Ontario and parts of Quebec) is primarily comprised of sedimentary rocks. Groundwater is obtained from unconsolidated aquifers (sand and gravel deposits of Pleistocene age) and consolidated limestone and dolomite aquifers.
- The Appalachian Region (New Brunswick, Nova Scotia, the island of Newfoundland, and Prince Edward Island) is characterized by mixed crystalline and folded sedimentary rocks and by flat-lying semi-consolidated sedimentary rocks (part of New Brunswick and Prince Edward Island). However, the generally fine-grained semi-consolidated flat-lying sedimentary beds are intensely fractured, which greatly contributes to their value as aquifers.

The areal distribution of the above physiographic regions is shown in Figure 7.

Groundwater is an important resource in Canada. Data collected by Hess (1984) show that approximately 33 percent of the Canadian population uses groundwater. Figure 8 illustrates the percentage of groundwater versus the total volume of water used by the population in each province. As can be seen, groundwater constitutes a very important resource in most provinces, which becomes even more significant when it is realized that 90 percent of the rural population relies entirely on groundwater (Hess, 1984).

III. IMPLICATIONS OF EXTRACTION OF GROUNDWATER

3.1 Introduction

Groundwater extraction by pumping from a well causes a lowering of the fluid potential or the hydraulic head in an aquifer (Fig. 9). The amount of decline is termed drawdown. The effect is strongest at the pumping well and decreases exponentially with distance from the pumping well. The area experiencing drawdown is called the cone of depression or cone of influence. With continued pumping the cone of depression deepens until a state of equilibrium is reached between inflowing groundwater and the pumping rate. The areal extent and the degree of deepening of the cone of influence is a function of the production rate, permeability, thickness, type of aquifer, available drawdown, size of the aquifer, rate of recharge, etc. For example, if all parameters are equal except permeability, the drawdown will be greater in the vicinity of the pumped well and less at great distances from it in the case of an aquifer with lower permeability.

By observing and measuring the change in the drawdown with time in observation wells completed in the aquifer at different distances from the pumping well, the safe yield of the aquifer can be determined. Several analytical methods have been developed for various aquifer configurations and boundary conditions to interpret the drawdown data (Kruseman and DeRidder, 1970; Walton, 1970). It should be realized, however, that most theories of aquifer analysis assume a high degree of uniformity in the aquifer characteristics and parameters, which is a condition rarely met in the natural environment. In spite of this drawback, the analysis and

evaluation of pumptests conducted in aquifers in unconsolidated sedimentary environments is sufficiently developed that reasonable estimates of the safe yield can generally be obtained. In many instances computer modelling graetly facilitates the aquifer interpretation, provided that the hydrogeological environment is well defined. This requires, however, not only that the modeller understands the limitations of the model, but also has a very thorough understanding of the geological environment he is dealing with. Unfortunately this combination of requirements is rarely met.

In contrast, interpretation of aquifer tests in fractured geological environments and karstic dolomites and limestones is still in its infancy (Gringarten, 1982). Similarly, groundwater flow in these media is not fully understood. This may in part be due to the much greater complexity of these environments compared to unconsolidated and semi-consolidated sedimentary environments, which in turn has resulted in slower advance of theoretical development. Futrhermore, the distribution of the permeability and its magnitude in space is due to post-depositional phenomena and not necessarily related to a specific lithofacies.In order to define the hydrogeological environment of such areas a much greater number of data points is required, which is inherently more costly. Accessibility is generally poor, which hampers the proper distribution of data points, and the material to be drilled often requires specialized drilling equipment. In addition much of the area underlain by potential fractured crystalline and sedimentary rock aquifers, at least 95 percent in Canada, is at best sparsely populated. Exceptions are Prince Edward Island and parts of New Brunswick and Nova Scotia. Furthermore,

especially in the largest crystalline rock region, the Canadian Shield, there is often an abundance of surface water. Similarly, the areas immediately underlain by karstic limestones and dolomites are in remote parts of the country, in the Mackenzie Mountains, the Yukon (Ford and Quinlan, 1977), the Great Bear Lake area, N.W.T. (van Everdingen, 1981), the Pine Point area, N.W.T. (Weyer, 1983), and northern Alberta (Ozoray, 1977 a and b).

However, remoteness or lack of population does not necessarily mean that no groundwater problems exist. This is illustrated by the experience of the mining industry in some of these areas. As mentioned before, several mines in fractured crystalline rock environments experience significant groundwater inflow. Individual rates range from 5×10^4 to 2×10^7 litres/day. The largest groundwater inflow in a mine in Canada known to the writer occurs in the Pine Point area (Weyer, 1983). The Pine Point ore bodies are located within karstic dolomite and limestone. In order to extract the ore, the ore bodies are dewatered. Daily groundwater extraction over the period 1971-1980 averaged 2 to 3×10^8 litres.

In the past the main concern of the mining industry with respect to groundwater inflow problems has usually been the size of the pump(s) required to get rid of the water and little attention was paid to the effect of dewatering on the regional environment. However, present environmental regulations require that this aspect is considered. Examples of detailed evaluations of the regional effects of major dewatering operations are the Cominco mine in the Pine Point area, N.W.T. (Weyer, 1983), the Saskatchewan Power lignite-fired thermal power plant in southeastern Saskatchewan (Int. Joint Commission, 1979), the open-pit Uranium mines in northern Saskatchewan, and the tarsand area of northeastern Alberta. All studies show that the areas

affected by dewatering range from several tens to hundreds of square kilometers.

The effects of karstification are not restricted to near surface environments. Salt karst developed and developing in the Prairie Evaporite Formation as a result of deep groundwater flow systems has resulted in the removal of the salt beds and subsequent collapse of the overlying strata (Holter, 1979; Baar, 1972; Christiansen, 1967, 1971; Gendzwill and Hajnal, 1971; Weyer, 1983). Where the collapse structures have not been healed subsequently by salt they represent highly permeable paths to groundwater flow. In areas where mining activity occurs, the "open" collapse structures represent potentially dangerous situations. Recently, in the Fall of 1984, one of these open systems was encountered at a mine of the Potash Corporation of Saskatchewan in southeastern Saskatchewan. The inflow of salt water was 2,500 L/min at the start and increased to 13,000 L/min ($3.6 - 18 \times 10^6$ L/day). At this time it is not known what the long-term effect of this will be on the mining operation.

Within the last ten years, major studies of groundwater flow within fractured crystalline rock environments have been initiated in Canada (Davison, 1984; Francis et al., 1984; Kohut et al., 1984; and Pearson, 1984). Several of these studies were initiated to determine the effect of the groundwater flow and subsurface geochemical environment on the long-term integrity of a repository for high-level nuclear waste located deep within plutonic rock in the Canadian Shield. It is hoped that the results of these studies will have universal applicability to flow in fractured rock. There is a considerable need for this type of information in order to properly manage the groundwater resources in fractured rock environments, not only in

Canada (the maritime provinces and especially Prince Edward Island, which obtains almost all its water from such an environment), but also in other parts of the world, for example India and many parts of Africa.

From the foregoing it is apparent that the effect of lowering of the fluid potential can be reasonably well predicted and projected in geological environments with intergranular groundwater flow, i.e. unconsolidated to semi-consolidated sedimentary environments, but the same is not true for fractured crystalline and sedimentary rocks and karstic environments.

It was mentioned previously that the lowering of the fluid potential results in a cone of depression. Under ideal conditions, in a homogeneous and isotropic aquifer, that is one with uniform permeability, of very large ("infinite") areal extent, the shape of this cone is circular in plan view. In a natural environment, however,the transmissivity (= permeability times thickness of the aquifer) generally has a directional distribution which is due to the type of depositional environment and depositional history of the sediments, preferred fracture orientations and variations in density and aperture, or directional occurrence of solution phenomena (karst). Extraction of groundwater from this type of environment will create a cone of depression which, in terms of shape, approximates the distribution of the directional transmissivity. This means that in fractured media and also in karstic terrain, which generally exhibits even stronger directional transmissivity, cigar-shaped to almost "linear" cones of depression can be expected. An approximation of the position and shape of a cone of depression can generally be inferred from the properly defined geological environment.

Knowledge of the shape, size, and areal distribution of the cone of

depression is important for groundwater management purposes (safe yield, interference, streamflow interception, saltwater intrusion, etc.) and environmental considerations (subsidence, contaminant transport, siting of waste disposal locations, etc.).

3.2 Groundwater - Streamflow Interaction

Water in steams (and lakes) originates as surface runoff, groundwater discharge, direct precipitation, and in places as municipal-industrial-agricultural effluent. Each stream has a groundwater discharge component, which is generally called the base flow. According to Newbury et al. (1969) the base flow receives its water from:

- transient bank storage,
- transient groundwater storage caused by rapid watertable rise following infiltration of precipitation, which is generally rapidly dissipated,
- groundwater stored within the sediments of the basin, which, according to the principles of groundwater flow, will move toward the topographically low area, i.e. the stream.

Freeze (1972) has shown that surface runoff in base-flow dominant streams is strongly influenced by the subsurface hydrogeological configuration, the saturated permeabilities of the formations, and the unsaturated soil characteristics of the soil types in the catchment basin. He further indicated the prominent role played by subsurface flows in generation of surface runoff. This mechanism can create such wide variations in watershed response to

precipitation events that simple functional relationships cannot be identified. Freeze (1972, 1974) suggests the use of more physically-based models to obtain more meaningfull interpretations.

In surface drainage basins where the chemistry of both the groundwater and surface water is known, the surface-water chemistry closely resembles that of groundwater during base flow periods. This is especially noticeable during the winter months when there is no direct surface runoff component. The variation in ionic content in a stream over a period of a year is primarily due to the dilution effect by fresh runoff water (precipitation and snowmelt). It follows therefore that excessive withdrawal of surface water from streams will result in a proportionally larger groundwater component in the stream. Because the ion concentration is generally considerably higher in groundwater than in surface water, this will result in a deterioration of the water quality of the stream for downstream users. The writer is not aware of any studies assessing the economic aspects of such a scenario. It is expected that, with the increased demand for "good" quality water, i.e. surface water, in western Canada, in the long term quality of stream and river water will deteriorate.

Figure 10 shows conceptually the relationship between groundwater discharge and streamflow for various river stages. Also shown is the effect of a pumping well close to the river or stream. If an aquifer is connected with a river, the lowering of the fluid potential can result in a reversal of groundwater flow, i.e. non-pumping flow toward the river and pumping flow from the river toward the well. The latter is called induced infiltration.

If a large volume of water is pumped from wells located near a river or stream, the streamflow will be reduced, not only as a result of induced infiltration, but also by the interception of the groundwater in the aquifer, which under non-pumping conditions would discharge into the river. It has, however, been found by the writer that in aquifers which are in direct connection with a river and receive most of their water from the river by induced infiltration, the infiltration capacity of the riverbed varies throughout the year. This is due in part to a decrease in the surface area available for infiltration, as a result of the lowering of the river stage. Secondly, due to reduced flow rates in the river, the sediment carried by the water becomes progressively finer (Blackford and Ongley, 1984), which results in finer material being deposited in the river channel. This in turn reduces the permeability of the riverbed material and hence the infiltration rate.

Damming a river to build a reservoir creates significant changes in the groundwater flow regime in the area. This phenomenon was investigated during the filling of Diefenbaker Lake in the South Saskatchewan River valley (van Everdingen, 1972 a). The results of this study showed that as a result of the additional head provided by the level of the water in the reservoir the groundwater flow regime was changed drastically. It has resulted in higher water levels (increased fluid potential) in the aquifers in the vicinity of the reservoir, causing some wells to start flowing. Overall vertical gradients below the reservoir have been reduced, with a resulting decrease in the rate of discharge from the aquifers to the river valley. Similarly, lateral gradients in several aquifers have been reduced, leading

to a decrease in the rate of groundwater movement toward the valley.

The above examples of interference by man in the interaction between groundwater-streamflow systems show that there is a direct cause-and-effect relationship with predictable consequences. Knowledge of this interaction has forced water management boards, especially in densely populated areas in the world, to consider the total resource of water, i.e. groundwater and surface water, in a river catchment basin as an integrated system, in order to properly plan the multiple use of water and avoid imbalances and consequently deleterious side-effects by overemphasis on one source only (Skinner, 1983). It appears that in Canada this approach is lacking in water resource management. This may be due to the fact that the densely populated areas in Canada generally occur in regions with abundant surface-water resources. Freshwater supply management has therefore traditionally concentrated on surface water. This approach still holds true for most of the country. For example,where a choice is available surface water will invariably be chosen over groundwater as a source. Although the vital link between groundwater flow and surface water flow has been proven many times in various parts of the world, it has received little attention in Canada. This may be due in part to a lack of understanding of the interaction between surface and groundwater flow, and in part to the fact that the existing data base is insufficient to show the long-term effects cf the modification of surface flow systems on groundwater supplies and vice versa. The insufficient data base is furthermore hampered by a lack of interest from the scientific hydrological community in long-term (10-20 years or more) projects to collect the necessary data, and by the lack of interest of

governments to commit funds for long-term studies.

3.3 Subsidence

Subsidence of the land surface occurs in many parts of the world. It is caused by tectonic movement, solution, mining, compaction of sediments due to static loading, vibrations, or increased density brought about by watertable lowering, and changes in reservoir pressure with loss of fluids (Domenico, 1972). Major subsidence attributed to the latter cause has been reported for various parts of the world. It is not restricted to groundwater withdrawal, but also occurs as a result of oil and gas exploitation. The maximum subsidence reported as a result of crude oil extraction is 8.8 metres at the Wilmington field in Long Beach, California (Yerkes and Castle, 1969). Gas fields which have shown subsidence are the Groningen gas field, the Netherlands (Schoonbeek, 1977) and the Po Delta gas field, Italy (Poland and Davis, 1969).

The best known examples of subsidence caused by groundwater withdrawal in North America are the Houston-Galveston area, Texas (Gabrysh and Bonnet, 1975) and the San Joaquin Valley in California (Poland et al., 1975).

In the Houston-Galveston area , an area of 12,200 km^2 subsided more than 0.15 metres. An area of approximately 45 km^2 shows subsidence greater than 2.5 metres. Several oil and gas fields are present in the same area and

their possible contribution to subsidence has also been investigated (Holzer and Bluntzer, 1984). It was found that of the 29 oil and gas fields only six caused additional local subsidence, but that the main cause of subsidence was groundwater withdrawal.

In the San Joaquin Valley, an area of 13,450 km^2 subsided more than 0.30 metres. The maximum subsidence which has been measured is 8.8 metres.

Subsidence creates serious and costly problems. The normal upward force of skin friction acting on piles or well casings may be reversed, which will subject these elements to "downdrag" (Domenico, 1972). This results in failure and collapse of casings and protrusion of structures above the land surface. Gradients in canals, for example for irrigation, and streams will be reduced or in the worst cases reversed, thus affecting the normal flow of water. Cracking of concrete or brick structures, sewer- and water lines is also likely to occur. In the San Joaquin Valley up until 1972 millions of dollars have been spent on the repair or replacement of deep water wells alone (Poland et al., 1975).

Subsidence is caused by the compaction of sediments, primarily clay-rich deposits. An increase in grain-to-grain load, i.e. an increase in effective stress, results in compaction. Terzaghi (1925) introduced the theory of effective stress:

$$p = p' + Uw$$

where p = total stress (geostatic pressure), p' = effective stress (effective overburden pressure or grain-to-grain loading), and Uw - pore pressure (fluid pressure or neutral stress). In a confined aquifer the lowering of the hydraulic head by pumping will not appreciably change the geostatic pressure

(Poland and Davis, 1969). Therefore, the increase in effective stress within confined aquifers is directly due to the decrease in fluid pressure (hydraulic head). This results in immediate compaction of the sediment, which in turn causes a partial loss of porosity. The magnitude of compaction is dependent on the compressibility of the sediments. However, if the fluid pressure is restored, much, but not all, of the compaction can be recovered due to the elastic nature of the sediment.

On the other hand, in clay-rich interbeds and confining beds with very low vertical permeability and high porosity, i.e. relatively recent sediments which have not undergone significant compaction, the vertical flow of water toward the aquifer induced by the lowering of the fluid potential is slow and the adjustment of pore pressures is also slow and time-dependent. Hence the stress increase in the fine-grained sediments induced by the lowering of the fluid potential in the aquifer becomes effective only as rapidly as pore pressure decay toward an equilibrium. This process may take months or years depending on the magnitude of the vertical permeability. The steady increase in effective stress (grain-to-grain loading) results in a gradual reduction of porosity, i.e. compaction of the fine-grained sediments. Since the initial porosity of these sediments is relatively high, generally much higher than that of the aquifer, a considerable volume reduction occurs in the very fine-grained clay-rich beds, which is the main cause of subsidence.

To arrest the compaction and thus subsidence, the hydraulic head in the aquifer has to be restored to such a level that it equals the maximum pore pressure in the confining beds and/or clayey interbeds. However,

due to various factors (Poland and Davis, 1969) which will not be further discussed here, the compaction of clay-rich sediments is not elastic and the initial porosity of the beds cannot be restored.

Proper investigation of a hydrogeological environment can generally predict the severity of subsidence.

Not much is known about areas in Canada where subsidence as a result of groundwater withdrawal may be causing major problems, nor is it known if oil and gas production may have caused significant, or at least measurable, subsidence. Logic suggests that this phenomenon should be occurring, but it has apparently not reached sufficient magnitude to attract attention.

One documented case of subsidence due to changes in the fluid potential was recorded by B.C. Hydro in the Downey Slide, which is located approximately 50 km north of Revelstoke, B.C. The slide is being dewatered continuously by means of drainage adits to avoid possible reactivation as a result of the presence of a newly constructed reservoir. The slide is composed of metamorphic rocks (mica schists, quartzites, etc.). A first order geodetic survey showed that dewatering over the period 1975 - 1984 resulted in a settlement of 6 cm. The watertable was lowered 100 m over an area of approximately 1 km^2, during this period.

3.4 Seawater Intrusion

Aquifers in coastal areas which are connected with the sea or ocean are subject to seawater intrusion. Figure 11 shows the idealized concept

of the freshwater-saltwater interface, the head distribution and the flow of both the freshwater and saltwater in a coastal aquifer. The contact between the freshwater and saltwater is generally not well defined and is characterized by a zone of transition. This is due to dispersion and diffusion effects. Dispersion is much enhanced by the back-and-forth movement of the water as a result of tidal and seasonal fluctuations (Van der Kamp, 1981). In areas where both fracture and intergranular permeability are present, the effect of dispersion is generally enhanced, because the flow takes place largely in the fractures, whereas most of the water is stored in the intergranular porosity.

The extent of the wedge of saltwater is determined by the hydraulic-head relationship between the seawater phase and the freshwater phase.

In coastal areas where multiple aquifers are in hydraulic connection with the sea, complex distributions of freshwater/seawater contacts often occur. This is illustrated in Figure 12, showing a cross-section located near York Point, beside the estuary of the North River, on Prince Edward Island (Van der Kamp, 1981). As can be seen in this figure, the salinities indicate various degrees of seawater intrusion. No groundwater is extracted from any of the aquifers in the immediate area. It appears therefore that the distribution of the saline water is entirely due to natural processes.

The landward flow of seawater in the deeper aquifers can be explained in part as the result of entrainment through dispersion (Kohout, 1960). However, variations in annual precipitation could also have significant effect on the position and movement of saltwater in coastal aquifers. Infiltration of rainfall and/or snowmelt to the water-table results in a

rise in the level of the water-table. This in turn provides additional head, which will result in "pushing back" of the freshwater/saltwater interface toward the sea. On the other hand, years with below average precipitation, i.e. recharge, will result in the opposite effect. Another possible explanation is the effect of rising sea levels. According to Dohler and Ku (1970), the sea level at Charlottetown has been rising about 30 cm per century. This means that the saltwater must be steadily penetrating farther inland in the aquifers because of both the coastline recession and the increased head of the seawater (Van der Kamp, 1981).

From the foregoing it is obvious that the freshwater/seawater interface is a dynamic entity and that its position is determined by the unique hydrogeological environment of the area. It is therefore also apparent that if the head in the freshwater flow system is changed by man, this will have an immediate effect on the position of the freshwater/saltwater interface. Figure 13 shows conceptually the change in the position of the seawater wedge in an unconfined and in a confined aquifer under pumping conditions. It should be realized that the movement of the freshwater/saltwater interface cannot be prevented. The rate of movement, however, can be controlled by the pumping rate, i.e. by the amount of change in the hydraulic head. The effects of seawater intrusion therefore become a groundwater management problem. Excess production will lead inevitably to contamination by seawater. Cessation of pumping will eventually re-establish the pre-pumping freshwater/saltwater distribution.

There are a number of methods available to control seawater intrusion (Kashef, 1971, 1975, 1976; Todd, 1974; Vandenberg , 1975). These methods

involve schemes where the position of the freshwater/saltwater interface is manipulated by recharge to and/or discharge from the aquifer in the area between the pumpwell and the coastline. Several of these schemes are outlined conceptually in Figure 14. Recharge methods to arrest seawater intrusion have thus far not been used in Canada. In other parts of the world, for example the West Coast Basin, California, the Biscayne aquifer, Florida, and dune aquifers along the coast in the Netherlands, recharge schemes are used effectively to prevent seawater intrusion.

Not all intruding seawater flows laterally toward a pumping well. In several instances upconing of seawater, or of saline water in non-coastal areas, has occurred toward wells where the freshwater aquifer is underlain by saline water-bearing strata (Todd, 1974; Streltsova and Kashef, 1974). The combination of leaky confining beds and the upward gradient created by the lowering of the hydraulic head in the well will cause this phenomenon. Reduction in the pumping rate is the simplest control method.

It is obvious from the foregoing that, with all parameters being equal, the safe production yield of an aquifer in a coastal area will generally be less than that for a similar aquifer in a continental region. To avoid the problem of seawater intrusion, the groundwater extraction rate has to be managed carefully. Alternatively, a control program to prevent seawater intrusion has to be employed.

3.5 Artificial Recharge

If the production from an aquifer exceeds the natural recharge, then the production rate is gradually reduced until a new equilibrium is reached, or a program of artificial recharge can be initiated.

Artificial recharge can be accomplished by either one of two basic methods: pit spreading and injection wells. In pit spreading, water is commonly diverted from a stream or released from a reservoir to shallow basins or trenches. The recharge water infiltrates through the bottom of the basin or trench and migrates downward to the water-table. Most spreading basins or trenches are modified to a rapid sand-filter system constructed on the natural soil material. When the infiltration rate declines, the basins are allowed to dry and are subsequently cleaned. Scraping, plowing, and disking are used to increase the permeability.

The infiltration rate is dependent upon the depth of the water in the basin, the vertical permeability, and the geochemical, biological, and physical changes that take place. To operate recharge ponds effectively, the water should be pretreated, primarily to remove sediment particles which can rapidly clog the sediment in the basin or pond. One of the main problems with recharge ponds or trenches is the growth of algae, which rapidly reduces the permeability of the sediments. The algal growth is primarily due to the fact that the surface water used generally has a considerable nutrient load. Covered seepage trenches have been used successfully in Germany to avoid this problem (Hantke, 1983).

The quality of the recharge water should meet drinking water standards.

It has very little sense to introduce contaminated water into the subsurface. Although the possibility of attenuation exists for certain constituents in a contaminant load moving through the subsurface, there is no guarantee that this will result in complete removal. In areas where urban storm-runoff is used for artificial recharge, for example in Fresno, California, it was found that significant amounts of lead, zinc, and copper had accumulated in the sediments in the retention basins (Nightingale, 1975). Studies of the soil profiles suggest that a considerable portion of the heavy metal load is retained by the soil. However, it is not known how much is being recharged to the aquifer.

Unwanted artificial recharge to the shallow subsurface is occurring in many irrigation districts. During the time of the year when the irrigation ditches and canals are filled with water they act in the same way as recharge trenches; in those parts of the ditches where significant permeability exists recharge occurs. This has led to loss of arable land due to salinization and alkalinization resulting from the combined effects of induced groundwater flow (i.e. a constant supply of ions)and evaporation.

The other method of artificial recharge is by means of injection wells. Such wells are used in localities where there are zones between the surface and the aquifer with such low permeability that vertical movement of water is too severely retarded. The injection wells are completed in the aquifer which is also used for groundwater withdrawal. Water used for injection has to be of high quality and chemically compatible with the aquifer water, otherwise clogging occurs (Warner, 1966, Rebhun and Schwartz, 1968). Other potential causes of problems with injection wells are:

- Suspended sediment. This has to be very low to avoid plugging of the pore spaces and/or fractures in the sediment around the well bore.
- Bacterial nutrients and bacteria. Slime formation in and around the well bore leads to clogging.
- Entrapped air. This causes clogging in the sediments surrounding the well bore.

It is obvious from the above that the level of treatment of water used for artificial recharge has to be much higher for injection wells than for surface methods. The greatest success with injection wells has been achieved in carbonate aquifers, which are less susceptible to the problems outlined above because of the presence of secondary (solution) permeability (karstification).

Infiltration basins for artificial recharge were first used in Germany in 1875 (Hantke, 1983). Since then various countries in the world have been using artificial recharge to augment their groundwater resources, to improve the quality of the groundwater, or to prevent seawater intrusion. In most countries, recharge is accomplished through sand and gravel. In Germany, Switzerland, Australia, and the Netherlands, basins and canals are preferred, whereas in Great Britain, Japan, Jamaica, and Israel, wells are primarily used. In the latter countries injection is mainly in carbonate aquifers. In the United States, U.S.S.R., and France, both basins and wells are used because of the wide diversity of aquifer formations being recharged (Brown and Signor, 1974). In some countries in western Europe, artificial recharge accounts for 20-40 percent of the total water requirements.

Artificial recharge has a number of advantages over surface storage schemes. These are:

- Elimination of losses through evaporation.

- Temperature equalization. River water temperature can fluctuate from 0 to 25° C. Heat exchange in the subsurface, depending on the residence time, reduces this range to about 8 to 15° C.
- Breakdown of organic compounds, denitrification and sulfate reduction. This occurs as a result of anaerobic and aerobic biochemical activity.
- Significant colour and taste improvement of surface water after passage underground.

In the past, it has also been assumed that bacterial and viral pathogens present in surface water would be destroyed after entering the subsurface. Recent studies, however, have shown that these bacteria and viruses do survive for prolonged periods of time in a groundwater environment (Bitton et al., 1983).

In areas where surface water/groundwater systems are managed as a single unit, artificial recharge is also used as a method to store excess runoff water which can then be extracted again during periods of low flow.

Experience in many parts of the world has shown that, although surface water has to be treated for artificial recharge, the total level of treatment is considerably less than that required for direct consumptive use of surface water. Furthermore, from the point of view of land use, artificial recharge storage schemes require only a fraction of the surface area that would be necessary for the equivalent volume storage in surface reservoirs. Also, artificial recharge is used successfully to replenish depleting groundwater resources in the world and at the same time to arrest the effects of subsidence and seawater intrusion that result from groundwater extraction.

Artificial recharge occurs in Canada mainly as a side-effect of irrigation. It is practiced to supplement groundwater resources in only a few areas, for example the Trenton-Aylmer area in Ontario and in Camrose, Alberta. The Camrose facility has successfully operated since 1958. Water is pumped from a lake into pits in a gravel terrace aquifer,at a rate ranging from 60-120 L/sec., to recharge the aquifer (Gabert, 1982). In Canada, when problems of groundwater supply are envisaged, the tendency thus far has been to switch to surface water supplies rather than to investigate the possibility of, for example, artificial recharge. Groundwater per se and groundwater flow are still considered by many as something mysterious and not as a commodity that can be dealt with in a rigorous scientific way and with an engineering technical approach. The attitude that "you cannot see it, therefore you cannot count on it" by civic administrations and (surface) water management groups has led to a reluctance to provide sufficient funds for a proper evaluation of the groundwater resources in many parts of the country. This is illustrated, for example, in the Kitchener-Waterloo region in Ontario (Farvolden, 1982). This region obtains its municipal water supplies from wells in Quaternary gravels. There is a justified concern that future needs cannot be met unless a new source is found. The favoured solution is a pipeline at a cost of several hundred million dollars to Lake Erie. However, it is felt by many geologists and engineers that additional groundwater supplies are available which perhaps are sufficient to meet future demands and which could be developed at a fraction of the cost of a pipeline. The problem is that there is an insufficient data base to properly assess the groundwater potential of the area. According to Farvolden

(1982, p. 68), " . . . Funds have not been made available for basic stratigraphic studies using modern techniques, and as a consequence hydrogeology cannot be used effectively in dealing with this problem. The inadequacy of geologic data is not limited to this region. Basic geologic mapping is lacking generally for assessment, development, and protection of our groundwater resources and somehow we have to convince government officials and funding agencies that it will pay to correct this deficiency . . . ". It is ironic that when funds are needed to define the geology for remedial measures after groundwater pollution has occurred, they are generally readily made available, but that there is great reluctance to spend money on studies which are directed toward prevention of such problems.

IV. GROUNDWATER CONTAMINATION

4.1 Introduction

Parallel with the physical flow of groundwater there is its geochemical evolution which determines the quality of the water that occurs at any point in time and space. The natural quality and composition of groundwater is determined by the type of soluble substances the water encounters, the distance it travels, its subsurface residence time, and a host of physico-chemical processes that involve both the water and the sediment matrix. On a local scale, groundwater is characterized by nearly constant chemical and physical properties. As a general rule, the dissolved solids content increases with depth. The chemical makeup is a direct reflection of the geological materials the water passes through, as is the evolution of its chemistry. Processes that control and may alter concentrations of solutes are: cation exchange reactions, complexing (chelation) reactions of metal ions with organic groups, specific adsorption of metal ions on mineral surfaces, specific adsorption of anions on mineral surfaces, adsorption of organic compounds, precipitation reactions, oxidation-reduction reactions, and various biochemical reactions. Most of these reactions are strongly influenced by the acidity (pH) of both the solute and the soil and sediment environment. For a more detailed review the interested reader is referred to Freeze and Cherry, 1979; Lindsay, 1979; Stumm and Morgan, 1970; and Tinsley, 1979. From the foregoing it is obvious that precipitation infiltrating into the ground enters a highly complex chemical environment, which will modify its original composition.

Use determines what standards will be applied to water quality. Different guidelines for water quality have been established for drinking water, industrial use, recreational use, preservation of marine or freshwater bio-communities, etc. (McNeely et al., 1979). Inherent in this approach is the assumption that a certain level of contamination will inevitably be present. The degree of contamination considered acceptable is generally determined by a cost-benefit analysis of downstream use. This implies that, because of political considerations, only short-term socio-economic benefits to society will be weighed. Long-term preservation of the quality of the terrestrial environment, which includes both surface water and groundwater, for future generations is often based on the blind hope that dispersion and diffusion of contaminants will suffice to maintain that quality. It is true that the natural environment has a tremendous capacity to absorb contaminants. Geological and biochemical processes operating in the natural environment generate very large quantities of substances classified by man as contaminants, which do not appear to cause major changes in the ecosystem. However, according to Fyfe (1982), man has become the greatest agent in modifying the surface environmental systems. The contribution to metal loading of rivers,and thus also the oceans, by the activity of man in most instances is an order of magnitude greater than that produced by natural processes. This is illustrated in Table 1.

Table I. Natural and man-made fluxes of metals into oceans (x 10^3 tons/yr), after Barney (1980).

	Natural	By Man
Iron	25,000	319,000
Manganese	440	1,600
Copper	375	4,400
Zinc	370	3,930
Nickel	300	358
Lead	180	2,330
Molybdenum	13	57
Silver	5	7
Mercury	3	7
Tin	1.5	166
Antimony	1.3	40

The additional influx of metals created by the activities of man will undoubtedly result in an adjustment of the bio-community in the receiving natural subenvironment with time. Geological history provides vivid examples of this type of evolutionary change. It is unfortunate that there is no appreciation of the potential magnitude of the long-term consequences of present activities, especially when it is realized that the present is the key to the future quality of the environment.

4.2 Groundwater Contaminants and their Movement

Groundwater is considered polluted when it contains dissolved chemical constituents which exceed the quality criteria for a specific use. The sources of these dissolved constituents are natural processes and/or the activities of man. Common usage appears to reserve the noun "contaminant" for those substances introduced by man which are deleterious to the quality of the natural environment. This usage will be followed in this paper.

There are many examples of naturally polluted groundwater, only a few of which will be mentioned here to illustrate its presence. These are: excessive amounts of iron, aluminum, zinc, lead, and copper in the Paint Pots springs, Kootenay National Park (van Everdingen, 1972b); salt springs along the contact between the Canadian Shield and the Western Sedimentary Basin (van Everdingen, 1971; Weyer, 1983); natural discharge of crude oil in the Petrolia area, southern Ontario; arsenic and uranium in groundwater in Nova Scotia; seawater intrusion in coastal areas; high manganese and iron content in induced infiltration water as a result of buried logs in river channel deposits in New Brunswick. A detailed discussion of pollution of groundwater by the natural environment is beyond the scope of this paper.

Groundwater contamination caused by the activities of man is the result of direct introduction of contaminants, mechanical failure of structures, lack of understanding of the natural environment, the "out of sight, out of mind" syndrome, lack of monitoring, lack of enforcement of existing regulations, unrealistic expectations generated by model studies of natural environments, etc. These observations will be further explained in the following sections of this chapter.

From the description of aquifers it is apparent that unconfined aquifers are most susceptible,leaky confined aquifers less susceptible, and confined aquifers least susceptible to groundwater contamination by direct introduction of pollutants to the subsurface environment. Furthermore, if the various geological environments are considered, fractured rock and sediment environments and those with secondary solution openings (karstic carbonates) are more readily contaminated than the environments with intergranular flow. Under the same hydrogeological conditions of head distribution, infiltration of contaminants as well as their lateral movement will be much faster in the former geological environments.

Contaminants are subjected to the same processes and reactions that affect the natural evolution of the groundwater chemistry, However, the reactivity of sedimentary environments with intergranular flow is much greater than that of fractured and karstic environments. This is due in part to the much greater surface area in contact with flowing groundwater and its dissolved constituents, and in part to the mineralogy of the sediments. All sedimentary deposits contain clays in various degrees of abundance, which are much more surface-active than, for example, the weathering products on fracture faces in fractured rock environments or on the surface of carbonates in solution channels. Attenuation of chemical constituents by the environment therefore plays a much more prominent role in sedimentary environments with intergranular flow than in the other geological environments. This also means that a sedimentary environment will show a residual contaminant concentration

much longer, after the main contaminant "plume" has moved through, than the other environments. An analogy may be drawn with, for example, the recovery of crude oil, where the primary recovery from limestone reservoirs is generally about twice as high as that from sandstone reservoirs.

The various ways in which contaminants can be introduced into groundwater are shown in Figure 15. It is obvious from this figure that a large number of possibilities for contamination exist. Miscible contaminants will be incorporated in a groundwater flow system and will move away from their point of entry under the same natural laws that govern groundwater flow. Immiscible liquids will move down to the water-table and spread on top of the watertable in the direction of its slope (Fig. 16).

The rate of movement of a miscible contaminant is identical to the rate of flow of groundwater. However, the distance a contaminant travels is a function of the degree of its attenuation. The overall effect is an apparently slower rate of travel. Contaminants will follow the same paths as the groundwater. This is illustrated in Figure 17, which is similar to Figure 4. The situations depicted in Figures 17a, b, c, and d are very common in the natural environment, both on a micro- and on a macro-scale, and especially in the more recent Pleistocene and Holocene sediments, which form the surficial cover over most of Canada. The rate of attenuation will be greatest in slightly permeable sediments (low K-values). However, in these sediments flow is essentially vertical and the distance of travel is generally short. Horizontal travel occurs primarily in the more permeably beds, where the degree of attenuation will be considerably less. Figure 17c shows a classic example of a stratigraphic trap. Contaminants that are retarded by

attenuation, hydrocarbons for example, would tend to accumulate at the contact between the high and low permeability beds, i.e. in the area where the highly pemeable bed stops. The greater the permeability contrast between the beds, the more effective the trap will be. However, as the flow lines indicate, flow is not stopped by these stratigraphic features, but continues. The effectiveness of the trap depends therefore on the chemical properties of the contaminant, the physico-chemical properties of the geological environment, and their interaction.

The foregoing examples also illustrate that the flow of water and the concomitant flow of contaminants in a heterogeneous geological environment will be concentrated in the most permeable beds. Dispersion and diffusion are generally restricted to a narrow zone around the contaminated body. The distribution of the contaminants in the subsurface generally reflects the (usually nonhomogeneous) permeability distribution. The widely accepted practice of representing contaminant fronts as large bodies spreading and dispersing uniformly through a geological environment is totally without foundation and shows a lack of understanding of the geological environment, and a lack of understanding of the limitations of data collection methods which are inherent in, for example, the type of drilling equipment used, the type and construction methods of sampling points, etc., or are due to insufficient quantity and quality of the data.

Without a proper definition of the hydrogeological environment, contaminant movement studies, computer modeling, and the design of remedial measures are analogous to a game of Russian Roulette.

As was mentioned before, groundwater flow will occur in time in all

sediments and rocks. No sediment or rock is impermeable on a geological time scale. Impermeability is a concept created by man because of an inability to grasp the effect of time over any period longer than his own existence. The concept of impermeability or the notion of "for all practical purposes impermeable" is being applied extensively in waste management, especially in the case of land disposal sites. Although the actual permeability measurements on samples may indicate extremely low values, these values do not take into account the possible presence of root canals, desiccation cracks, fracturing, etc. The significance of these features should not be ignored, because they provide the primary escape routes for contaminants from a disposal basin. This is illustrated in the following examples.

Several years ago, a major mining company installed, with great care and at a considerable cost, a polyethylene membrane in a waste disposal basin, several hundred acres in size, to make it impermeable. But, as one of the engineers pointed out, complete integrity of the liner could not be guaranteed, because there would undoubtedly be a few pinholes. He estimated that the loss of liquid waste through one pinhole, 3 mm (1/8 inch) in diameter, depending on the liquid level in the basin, could amount to several thousand gallons per year. After the basin was operated for a few years, his predictions were proven correct: significant groundwater pollution did indeed occur.

Many shallow confined aquifers show a low barometric efficiency. Barometric efficiency is a measure of the response of the water level in a well to changes in the barometric pressure (Jacob, 1940). For truly elastic, homogeneous, confined aquifers the barometric response would be 100

percent. However, if the aquifer is semi-confined, in other words if the "confining" beds are leaky, barometric efficiency values are considerably lower than 100 percent (Gilliland, 1969). The writer found values ranging from 9-32 percent in a so-called confined aquifer located at a depth of 10 metres (Vonhof, 1983). The "confining" layer was till. According to Grisak and Cherry (1975), the intergranular permeability of till based on a large number of core samples ($<$ 20 cm in diameter) is 5×10^{-9} cm/sec, i.e. for all practical purposes impermeable. This value falls well within the range of the permeability of clay (Freeze and Cherry, 1979). An examination of borrow pits in the area investigated by the writer showed that the till was fractured (Vonhof, 1983), which meant that the permeability of the till was several orders of magnitude greater than the above mentioned value. This would also explain the "leaky" character of the confining layer as indicated by the low barometric efficiency. Brine stored in a waste disposal basin located on top of the (leaky) till has in the meantime entered the underlying aquifer.

The above two examples are given to show the relativity of the term "impermeable" in waste disposal basins. In the first case a concerted effort was made to make the basin impermeable, whereas in the second case the values derived from measurements of intergranular permeability were considered in isolation from other features of the sediment. The end result in both cases was significant groundwater contamination. Experience indicates that these examples are not isolated cases; unfortunately, they appear to be the rule rather than the exception. Adherence to the concept of impermeability will guarantee major environmental problems for future generations.

It should be realized that storage in the surface environment, of liquid waste or of solid waste not properly protected from the elements, only delays its re-entry into another part of the natural environment.

Many instances of groundwater contamination from waste disposal in Canada are the result of past activities. Present environmental laws and regulations in most provinces are such that groundwater pollution can be prevented, or at least restricted to the immediate area of a disposal site, if waste disposal basins are monitored properly and if the regulations are indeed enforced. In the writer's experience, most industries are good corporate citizens and generally comply with the level of effort required by government. However, in addition to point-source contamination by liquid and solid wastes there is a continuous, diffuse input of chemicals introduced by agricultural practices and acid rain, which has the potential to cause large-scale contamination of groundwater with time.

In the following sections groundwater contamination from a number of sources will be discussed. This is by no means a detailed discussion, but an overview only.

4.3 Mining

Mining, like any other activity of man, causes environmental contamination. To require zero effect would be totally unrealistic and would render all mining operations uneconomical. However, by proper management the degree of contamination can be significantly limited without seriously affecting the economic viability of the operation. A somewhat greater

degree of freedom for environmental management exists in the mining industry as compared to other industries, because many mines are located in remote parts of the country with few, if any, other users of the same environment. Also, general background levels of the particular commodity mined are in several cases already considerable in the natural environment where the mine is located. This phenomenon, in fact, is the basis for the geochemical exploration techniques used by mining companies.

The main sources of environmental contaminants in mining operations are atmospheric emissions, mine drainage, tailings disposal, discharge water from the extraction phase, and discharge water from the beneficiation phase. Although atmospheric emissions are not a direct cause of groundwater contamination, they do represent a potential source after deposition on the land surface, either as particulate matter or incorporated in precipitation. The composition of the emitted particles and gaseous material will vary depending on the type of ore mined and the processing method employed. The emissions will result in elevated levels of various metals in the soil and acid rain.

The total land area disturbed and utilized by the metallic and non-metallic mineral sectors (excluding construction materials) is about 112,260 hectares. Smelter and refinery operations located on industrial sites within urban centres utilize an additional 7,670 hectares (Marshall, 1982). It is estimated that in the next twenty years and additional area of approximately 60,000 hectares will be disturbed by the mineral sector. In addition, the energy-related sector of mining has affected about 34,000 hectares of land. A projected three-fold increase in surface mined coal over

the next twenty years will result in an additional land disturbance of between 18,000 to 20,000 hectares (Marshall, 1982). Part of the land disturbed by mining will be reclaimed. In addition to the land directly disturbed by the mining operation , mining can also have a considerable influence on the land surrounding its operation. This influence is referred to as the "shadow effect" (Marshall, 1983). It would include lands affected by atmospheric emissions and the area affected by contamination of both surface and groundwater. The size of the area thus affected may be many times greater than the actual mine site or lands within the operational control of the mine.

In 1980 (E.M.R., 1981) the total volumes of ore mined and waste generated were 290 x 10^6 tonnes and 445 x 10^6 tonnes respectively.

Metal mining. The main environmental concern of metal mining and milling operations is the accelerated introduction of metals into the environment. Contaminated water from mining activities is primarily associated with mine drainage, leachate from tailing storage areas, mill water, and waste solutions released in the hydro and electro-metallurgial processes.

Mining increases the surface area of rock. This in turn results in increased exposure of minerals to oxidation. Bringing sulphide minerals into contact with water and air promotes a chemical reaction which results in the formation of sulphuric acid, which in turn will increase the dissolution rate of metals and hence their mobility in the environment. Note: not all mines have acid mine drainage problems; in Canada such problems are normally only associated with sulphide-bearing metallic ores (Marshall, 1982).

Introduction of specific species of bacteria to extract metals from low-grade ore is a promising technique and is used successfully at a number

of mine sites. The main group of bacteria used is Thiobacillus ferrooxidans. It uses sulphur and iron in the presence of water and oxygen in its metabolic system to extract energy, and it creates sulphuric acid as a waste product, which in turn dissolves other more valuable metal sulphides. However, the environment of these bacteria is not restricted to ore zones. As a result, other parts of the mine, as well as tailing piles that contain iron sulphides, can be infected.

The mine drainage water which often contains significant quantities of toxic dissolved metals is stored at surface in ponds. Part of this water may be recycled for use in the mining operation. Prior to the release of the effluent water to the environment the water is treated to neutralize the acids, remove heavy metals, and radioactive substances where present. Losses of water from impoundment areas occur as a result of evaporation, runoff, seepage, and percolation.

Beneficiation of ores results in additional potential contaminants, created by the mining industry, which have to be isolated in the environment. Mill tailings, generally very finely ground material, together with effluent water from the mill is disposed of in impoundment areas. The slurry invariably contains a small percentage of the constituents of the original ore and small quantities of organic reagents used in the mineral processing. The reagents include frothers, collectors, depressants, pH modifiers, activating agents, flocculants, coagulants, and dispersants (Marshall, 1982). Although recycling of effluent water has drastically reduced the volume to be disposed of, most water is eventually discharged to impoundment areas. Many reagents are highly toxic and lethal to some organisms (Hawley, 1977).

Waste disposal practices, properly managed and enforced at existing mining and milling operations, generally do not present a major threat to the environment over the lifetime of their operation. Problems do, however, occur after the mine or mill has been abandoned and in areas where mining activity was started prior to the passing of the environmental regulations by the various levels of government. In many of the older mining districts in Canada tailings and effluents were dumped in areas of convenience rather than in environmentally safe areas. Furthermore, bacterial growth, oxidation, infiltration of precipitation, geochemical processes, and groundwater flow in abandoned mines and tailing piles and ponds continue and these have led to serious problems of contamination. Ample evidence of this is available in all old mining districts in Canada. In most instances where problem areas have been recognized only the contamination of the surface water environment has been documented, for example Giant Yellowknife, Cominco Con, Echo Bay, and Canada Tungsten mines in the Northwest Territories (Wallace et al., 1975); the Flin Flon area, Manitoba (Rowley, 1975); and Serpent River Basin, Ontario (Roy & Keller, 1976). An example of a case where groundwater contamination is suspected but has not been documented is the Canada Tungsten mine in the Northwest Territories (Wallace et al., 1975). Overflow from the tailings pond was discharged into a gravel pit. Wallace et al. (1975) report that "Due to the porosity of the bottom and sides of the gravel pit, the fluid was lost to the water table and could not be visibly traced".

Examples of serious acid mine drainage problems caused by uncontrolled bacterial growth and tailings pile infestation can be found at the Britannia Beach mine and the Equity silver mine, respectively, in British Columbia

(The Calgary Herald, December 5, 1984). Millions of dollars are being spent at the Equity silver mine to correct the bacterial infections, which unfortunately are very difficult to kill. Furthermore, the compounds used to combat these infections are highly toxic to the environment and could thus present an additional problem.

The aspect of groundwater contamination near mining operations has, based on a survey of the published literature, received little attention in Canada. It is nevertheless reasonable to assume that groundwater contamination is occurring in all mining districts where tailings and effluent water were disposed of in an environmentally uncontrolled fashion. Lack of data precludes any estimate of the extent and degree of groundwater contamination in the mining districts. Similarly, the long-term effect of groundwater contamination on the surface water resources in a given area is difficult to assess, especially if it is considered that the natural subsurface environment has a large capacity to attenuate several metals and other dissolved chemical compounds.

Reclamation of abandoned mine and mill sites in the older, but still operating, mining districts in Canada is going to require hundreds of millions of dollars. Today reclamation is considered an essential part of resource management and regulations and policies covering this aspect in one form or another exist in all provinces. A number of joint work groups of representatives from various levels of government have been created to examine different aspects of land reclamation.

A backlog of several tens of thousands of hectares of land disturbed by mining exists across Canada. In many instances, funding to investigate and

assess the extent of environmental damage, both in terms of the surface and the subsurface environment, and to cover the cost of reclamation will have to be provided by governments, either provincial, federal, or both. This is necessary, because unfortunately in a large number of cases the companies that conducted the mining and milling operations which caused the current problems no longer exist. In several provinces, for example Ontario and Quebec, environmental management of abandoned mine sites has therefore been taken over by the government. The long-term implications of mine waste will be addressed further in another part of this paper.

Coal mining. Coal mines differ from metal mines in that the direct introduction of metals into the environment is usually negligible. This does not mean that coal does not contain metals; on the contrary, coals are known to contain a very large number of metals in varying concentrations. These are released during burning. A portion of the metals is trapped in fly ash, the remainder enters the atmosphere and returns to the surface by fallout.

Most coal contains sulphur, from a fraction of a percent to several

percent. Oxidation or bacterial conversion of the sulfur can cause acid mine drainage problems. The severity of such problems depends on the longterm buffering capacity of the environment.

Coal, like other minerals, may be mined by open-pit or underground methods. In open-pit mining the sediment between the zone of interest and the surface is removed. This often results in the physical destruction of aquifers. Unlike to open-pit metal mines, most open-pit coal mines are filled in and the land reclaimed. Although it is theoretically possible to reconstruct the aquifers, cost-benefit analysis will show that it is invariably uneconomical to do this. Backfilled open pits therefore act as a facies change in the lateral continuity of sedimentary beds. Since the fill is heterogeneous, the possibility of cross-formational flow between aquifers exists. Depending on the chemical composition of the waters and the resultant direction of flow, this may be beneficial or detrimental. Also, the fill generally contains a higher percentage of soluble material than the original aquifers, which can result in an increase in the dissolved ion content of the groundwater with time (Moran and Cherry, 1977).

Underground coal mines as a rule are not backfilled. After mining the roof is allowed to collapse. This will cause fracturing of the overlying beds and changes in groundwater flow patterns in the area, which could result in increases in mine drainage. If the water is oxygenated, this will result in accelerated oxidation of sulphur compounds. After abandonment the problems of acid mine drainage can be similar to those in metal mines.

Where large quantities of ammonium nitrate-based explosives are used,

contamination of the environment by these compounds can also occur (Weyer and Vonhof, 1980). It appears that the longterm environmental effects of (reclaimed) open-pit mines are less than those of underground coal mines.

Potash mining. Potash is being mined in Saskatchewan and in New Brunswick. Both liquid and solid granular wastes are generated (Vonhof, 1983). The waste, sodium chloride, is generally stored in waste disposal basins. At most mines in Saskatchewan part of the liquid waste is disposed of by deep-well injection, whereas a pipeline to the Atlantic ocean is being planned for the mines in New Brunswick. The solid waste is generally stacked, forming some of the more significant topographic features in Saskatchewan. The combined area of the waste disposal basins in Saskatchewan is approximately 35 km^2, containing about 200-300 million tons of sodium chloride and growing daily.

Brine has infiltrated the subsurface at every disposal basin and this has resulted in local groundwater contamination. To limit the spread of groundwater contamination, which at a number of mines could also result in contamination of major freshwater aquifers or surface water resources, slurry cutoff walls had to be installed.

Originally it was thought that the solid waste could be returned underground in the rooms left behind by mining. However, the mined areas close slowly with time due to the viscous flow behaviour of salt (Baar, 1977).

If granular salt is piled high enough, recrystallization will occur at the bottom. Once the bottom layer is recrystallized, it becomes essentially an impermeable layer, thus preventing further groundwater flow into the underlying sediment. It was hoped that by stacking the waste salt this

condition could be achieved in Saskatchewan. According to Maathuis (personal communication, 1985), a height of 50 metres may be required. Even if this phenomenon did occur, observations by the writer and others (Maathuis, van der Kamp, personal communication, 1985) show that the salt is rife with solution channels. This is due in part to the method of waste discharge into the basin and in part to the fact that precipitation causes solution karst. Furthermore, the fine-grained sediments that underly the waste salt are subjected to compaction by the loading of the waste salt pile. "Fresh" water expelled during this process will dissolve salt at the base of the pile (Maathuis and van der Kamp, 1983).

The total volume of brine produced per year by the petroleum industry in western Canada is comparable to the waste salt production of the potash industry (Zenon, 1983). However, the petroleum industry is not allowed to dispose of any of its brine in the surface environment.

4.4 Oil and Refined Petroleum Products

The potential impact on the environment of onshore Canadian oil and gas drilling and production was recently reviewed by Zenon (1983). Drilling and primary production generally have a low level of impact except when a major blowout occurs, as recently happened at the Amoco sour gas well near Drayton Valley, Alberta. Brine contamination of the shallow subsurface is a problem at some of the old battery sites, but this is generally due to the operating practices prevailing at the time, when environmental regulations were not as strict (de Jong, 1980). Prior to abandonment of a site, industry has to clean up

before approval is given by the regulatory agencies in the producing provinces.

Of greater concern are the potential problems that can arise from enhanced oil recovery projects. In enhanced recovery, special techniques are used to recover the oil left in place after primary and secondary recovery have become uneconomical. Methods used are chemical, thermal, and miscible flooding. The waste products generated during miscible flooding are in general similar to those of conventional oil production and their environmental impact is low under normal and proven operating practices. The most serious waste problems appear to be connected with chemical flooding, because of the toxicity of the chemicals used (Zenon, 1983). However, this process is still in the experimental stage. Thermal flooding is used extensively in the recovery of heavy oil. There are a number of problems associated with heavy-oil production. These are:

- Sand production. This ranges from 0.5 to 10 percent of the volume of oil produced. The sand will be coated with a thin film of oil or solvent if a further recovery of oil is attempted. The sand is presently used in road paving, but it is expected that with large-scale development of heavy oil fields the sand will have to be stored, which could lead to groundwater contamination. Proper placement in the hydrogeological environment therefore becomes very important to minimize migration of contaminants.
- Subsidence. As a result of the removal of large quantities of sand, subsidence can occur around a well head, which in turn may affect the integrity of the well bore and/or the confining beds. This could

lead to cross-formational flow and contamination.

- Liquid waste. The water produced with the oil and during the upgrading of the oil cannot be discharged to the environment. Present plans are to re-use part of the water and dispose of the remainder by deep-well injection. Whatever is injected in northeastern Alberta and the adjoining area in Saskatchewan will flow in a northeasterly direction, following the regional direction of groundwater flow. Liquid waste injected in Alberta will ultimately end up in Saskatchewan. Although a three-dimensional groundwater flow model for the Cold Lake area has been developed by the Alberta Research Council in cooperation with Esso Resources, the study was concerned only with local effects and did not address inter-provincial effects.

In addition to deep-well disposal, some of the liquid waste, for example sludges, will be disposed of in ponds. It is difficult to assess the potential impact of the various liquid wastes, because little is known about their composition, volume, and toxicity, and further studies will have to be undertaken.

The impact of gas processing plants on the environment is presently undergoing intensive review in Alberta. New regulations governing all aspects of the environment are expected there in the near future.

Spills of refined petroleum products, such as aviation fuel, gasoline, diesel fuel, etc., caused by spillage, breaks in pipelines, or leakage from underground tanks, generally receive the greatest amount of attention. Infiltration of petroleum products into the shallow subsurface and their subsequent movement can result in groundwater pollution, explosions, fire

hazards, and health hazards (Vonhof, 1977). The effects can be local or widespread. The worst case in Canada occurred in St. Eustache, Quebec in 1978. Gasoline leaking from an underground tank spread over a large area, seeped into sewage lines and resulted in explosions. More than 2000 people had to be evacuated and the total cost of evacuation, cleanup, and rehabilitation was well in excess of one million dollars.

In most cases, fire and explosion hazards are the primary concern. However, in areas where groundwater is an important resource, a petroleum-product spill can be devastating. One litre of gasoline can easily contaminate one million litres of drinking water. Treatment procedures are available, but costly. In Europe, where 75 percent of the population relies on groundwater, contamination by petroleum products is considered very serious, and spills generally result in immediate action by government.

Petroleum products, once incorporated in the subsurface and in the groundwater flow system, are extremely difficult to remove. Whatever in-situ method is used for cleanup, there will always be a residual component. The volume of the residue is a function of the geological environment, and will be much greater in sedimentary deposits than in fractured rock or sediments with secondary solution openings. Primary recovery in sedimentary deposits is generally in the order of 30-50 percent, and may be considerably higher in the other environments. The residual concentration can contribute to groundwater pollution for a long time. There are documented cases in Europe where petroleum products have been a source of groundwater contamination for more than 50 years (Zimmermann, 1967). Cleanup measures are invariably long term and costly procedures. Governments that have recognized this fact and

also understand that contamination of groundwater not only destroys a vital freshwater resource,but will inevitably lead to a reduction of surface-water quality, have put their main emphasis on preventive measures to avoid groundwater contamination. For example, mandatory testing of both private and commercial storage tanks, on a regular basis, is common in many countries in Europe. Inventory control is strict, and abnormalities are to be reported to the authorities immediately. Cathodic protection is mandatory in many areas; vaults are used in groundwater sensitive areas, etc.

In Canada, company owned distribution centres and service stations are generally well managed. Most problems occur at owner-operated stations. Although inventory control is required by regulation by several provincial governments or by companies supplying products, and although it certainly should be practiced by the owners for reasons of good housekeeping, it is generally not actively enforced. Inventory discrepancies are almost always discovered after a major problem surfaces. In many instances the financial resources of the owner-operator are limited. This means that a third party, generally the government, has to first assume the cost of any investigation and remedial measures, with the hope of recovering some of the costs later. Damages incurred by other parties may or may not be recoverable at all.

In most instances, underground leaks are caused by corrosion of unprotected storage tanks. It was estimated in the late seventies that 48,000 unprotected buried tanks were present in Ontario alone (Canadian Water Well, 1985) The total number of unprotected tanks in Canada is not known, but it is estimated to be well in excess of 100,000. Although replacement programs are in effect in many provinces,it appears from the numbers involved that a considerable number of underground leaks will still occur in the foreseeable future.

4.5 Industrial Sources and Landfills

Groundwater contamination caused by various industries other than those described above is difficult to define, because potential contaminants are often unique to the type of industry and their effects on the subsurface environment are site-specific.

Many industries discharge their waste to municipal sewer systems where, after treatment, it is released to the surface environment or is concentrated in sewage sludge. Sludge is generally disposed of by land spreading. Sludge is a valuable source of nitrogen and phosphorous, but it generally also contains a host of heavy metals and occasionally toxic organic compounds. Metals which commonly occur in sludge are cadmium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, selenium, silver, tin, and zinc. The sources of these metals are domestic and industrial sewage and storm runoff. The metals are retained by the soil after sludge application. Repeated application of sludge will lead to an incremental build-up of these metals in the soil. Uptake of part of the metals by plants can make the plants toxic to livestock and humans or, where excessive concentrations of the metals are present in the soil, the soil itself may become toxic to plants (Bates, 1972).

Soil contamination by metals and other chemicals is not restricted to sludge application. Industrial smoke stacks, vehicle exhaust, dust particles, etc. all represent potential sources. For example, elevated levels of nickel, copper, and zinc were found in soil downwind from nickel smelting operations at Coniston, Ontario (Rutherford & Bray, 1979); fluorine levels increased downwind from aluminum smelters in the St. Laurence valley, Cornwall, Ontario,

and the Lac Saint Jean region, Quebec (Simpson Lewis et al., 1983); and increased sodium and potassium levels are found in the soil downwind of the potash mines in Saskatchewan.

The extent to which groundwater may become contaminated with heavy metals from sludge applied to soil is dependent on the heavy metal content of the applied sludge, the loading rate, the physico-chemical properties of the soil, the texture of the soil, the distance to the water table, and the precipitation rate. Most metals appear to be fixed by the soil and thus become immobilized. The threat of groundwater contamination therefore appears to be minimal. However, continuing input of acid precipitation may alter the present equilibrium and remobilize those metals. The total area which receives sewage sludge in Canada is not known, but Ontario alone uses approximately 11,000 hectares (Simpson Lewis et al., 1983).

Landfills, although primarily designed to receive domestic garbage, also receive a considerable amount of industrial waste and are therefore included in this chapter.

The total amount of garbage generated in Canada is about 15×10^6 tonnes per year. Toronto alone produces approximately 1.4×10^6 tonnes per year, which would cover a land area of 40 hectares with a 3 metre thick layer (McKechnie et al., 1983).

Leachate produced in the landfills is the main environmental concern. Runoff from landfill sites or infiltration of leachate into the shallow subsurface can seriously affect the quality of the receiving water. Leachate is produced by the decomposition of organic compounds and as a result of direct introduction of water which dissolves soluble matter. Water enters

landfills as precipitation, groundwater inflow, surface seepage and runoff from surrounding land.

The composition of the leachate is controlled by the types of waste deposited. Decomposition of ordinary municipal waste produces methane, carbon dioxide, water, various organic acids, nitrates, chlorides, calcium, manganese, iron, ammonia, etc. In ordinary municipal waste the leachate strength is attributed to textiles, rubber, leather, wood, paper, and cardboard (McKechnie et al., 1983). All landfills receive a certain percentage of hazardous waste from regular household use (solvents, cleaners, metals, etc.). It appears, however, that the diffuse distribution of this material within the landfill does not present a serious problem.

In properly managed landfill operations leachate production is kept to a minimum. This is achieved by proper siting of the disposal area in the hydrogeological environment, modification of the surface runoff pattern, and elimination of infiltration of precipitation. The latter is achieved by placing clay caps on the refuse shortly after the waste has been deposited. Furthermore, operational practices in present-day landfills tend to isolate volumes of refuse in separate cells and the waste in each cell is bounded on all sides by clay or clay-rich sediment.

In hydrogeological settings where leachate is expected to be a problem, contamination of the groundwater can be limited by the installation of drains, cut-off trenches, and pumping wells. The leachate recovered will have to be treated prior to discharge into the surface environment.

In the past, hazardous wastes were indiscriminately dumped in landfill sites across the country without any regard to the environment in which the site was situated. Furthermore, many landfill sites were located in abandoned

gravel and sand pits, rock quarries, and convenient natural depressions, such as gullies, sloughs, coulees, swamps, etc. Examples of this type of disposal can be found in the countryside in all provinces and territories.

One of the worst cases of contamination of groundwater by industrial waste has occurred in the region of Mercier, Quebec (Poulin et al., 1984). About 40,000 m^3 of liquid wastes from chemical and petrochemical industries in the Montreal area were disposed of in a gravel pit. This has resulted in groundwater contamination over an area of 30 km^2. The main contaminants are chloroform, dichloroethylene, trichloroethylene, dichloroethane, trichloroethane, chlorobenzene, phenols, and BPC (arochlor 1254 and 1260). It is expected that it will cost the Quebec government in excess of 10 million dollars to recover and treat the waste and provide water from another source for the inhabitants of the region.

Under current environmental legislation in the various provinces, new landfill sites and industrial waste disposal areas require a definition of the hydrogeological environment, monitoring programs, and, where necessary, installation of impermeable membranes or clay layers and drainage systems.

All provinces have embarked on waste-site identification programs and risk assessment of the sites of old waste disposal locations and landfills. Criteria used in the risk assessment include type of waste disposed of, physical setting with respect to surface drainage, and location within the hydrogeological environment. The surveys are at this point in time at various levels of completeness, both in terms of inventory (abandoned landfills, active landfills, or both, or all waste disposal sites) and the level of information on each site. For example, Ontario has identified approximately

1400 sites which were closed before 1971. Of these, 197 with the greatest potential for environmental impact were studied in more detail. In only three cases were off-site impacts observed. Currently the active landfill sites are being evaluated. Four hundred waste disposal sites have been identified in Prince Edward Island. Based on a priority rating, 22 sites were investigated in detail. No off-site impacts were observed. In Quebec a detailed survey of waste disposal sites has been completed. The type of waste as well as potential impact on the groundwater and surface water resources has been identified. Further investigations will be conducted around these sites to determine the extent and degree of groundwater contamination. In an area with a radius of approximately 35 km around Montreal, 50 sites were identified. One of these sites, at Mercier, was discussed previously. Saskatchewan has inventoried all its abandoned and active landfill sites, but hydrogeological investigations have only just commenced. In Alberta all landfill sites have been identified and rated with respect to their potential effect on the environment. Hydrogeological investigations have been conducted at several sites. Leachate problems have been detected at a number of these.

Most provinces have designated portions of existing landfill sites to handle hazardous toxic wastes, or they are planning special landfill sites which can accept this type of waste either in storage or for further processing to render it harmless (Alberta, Ontario, and Quebec). The Alberta facility will be located in the Swan Hills and will include a deep well disposal system. In most instances, the special landfill sites will be operated by crown corporations.

From the foregoing it is obvious that it is not possible at this time

to assess the environmental impact of all the old industrial waste-disposal sites and abandoned landfills in Canada, because the data base is insufficient and incomplete. No cost estimates of clean-up can be made at present.

Experience with the U.S. Superfund indicates that major remedial work will be necessary at more than 400 industrial waste-disposal locations. At about 25 percent of these sites, which are primarily chemical and petrochemical waste dumps, expenditures will be in excess of 1 million dollars. Ontario has estimated, based on proportionality of population between the U.S. and Canada, that about 19 million dollars would be required in that province alone MOE, 1984). For Canada as a whole this would mean a total in the order of 60 million dollars. If it is considered that the clean-up bill of the Mercier site in Quebec is 10 million dollars (minimum), and estimates of individual sites in the U.S. are several tens of millions of dollars, it appears that the Ontario estimate is optimistically low. To generate sufficient funds for clean-up of abandoned waste disposal sites, Ontario is considering the creation of a waste management security fund. The fund would be built up by a surcharge on disposal fees at approved waste management facilities. In addition, the government of Ontario is considering to require operators and owners of waste management facilities to carry environmental impairment insurance and/or the posting of financial guarantees (MOE, 1984). The approach suggested by Ontario operates on a "user pays" basis. The fund will be used to cover costs of environmental emergencies at active disposal sites, provide funds for perpetual care of toxic waste, and moneys to clean-up abandoned sites. It is expected that the other provinces will follow a similar approach for their waste management.

4.6 Agriculture

Sources of groundwater contamination by the agricultural industry include animal feedlots, manure piles, pesticide, fuel and fertilizer storage, and land application of fertilizers and pesticides. In addition, dryland crop-fallow rotation practices can cause significant changes in the water quality of aquifers.

Animal feedlots, manure piles, and leaking septic tanks can cause significant groundwater contamination problems by introducing nitrate, chloride, organic carbon,and ammonia, as well as bacteria and viruses. Although attenuation of the carbon, ammonia, and bacteria concentrations does take place in the unsaturated section of the soil, overloading will result in downward movement.

Groundwater contamination as a result of storage of pesticides or fertilizer is usually primarily due to poor site selection and poor housekeeping practices, but can also be the result of an unforeseen accident. An example of the latter occurred recently in Prince Edward Island: during a fire in a storage shed a considerable quantity of pesticides was dissolved during attempts to extinguish the fire. This resulted in local contamination of the subsurface.

If application of highly soluble (nitrate) fertilizers takes place under unfavourable soil conditions, i.e. light-textures soils with high infiltration capacity, contamination of the groundwater in water-table aquifers will take place. However, it has been found that, if the water-table is shallow and downward transport of organic carbon (which causes a reduction of dissolved oxygen in the water) takes place, denitrification of the nitrate by anaerobic

bacteria occurs in the aquifer (Hendry et al., 1983; Gilham et al., 1984). This process results in a significant reduction of the nitrate content in the aquifer where the water-table is shallow. In parts of the aquifer with a relatively deep water-table little or no denitrification occurs (Gilham et al., 1984). Another process that can cause high nitrate concentrations in water-table or unconfined aquifers is oxidation of organic nitrogen (Kreitler & Jones, 1975). However, this only occurs in areas where plants are grown that fix nitrogen.

In many parts of southern Alberta very high nitrate concentrations have been found in the shallow subsurface. The distribution of areas with high nitrate is restricted to oxidized tills. Studies conducted by Hendry et al. (1984) show that this nitrate originates from aerobic bacterial processes, which convert exchangeable NH_3 present in the unoxidized till. It appears that NH_3 is indigenous to the sediment. If this is true, then it is possible that many areas of the Prairies could have similar nitrate contamination of the shallow subsurface.

Pesticides are used extensively by the agricultural industry. They comprise a group of chemicals highly toxic to man and their use is therefore relatively strictly controlled. However, it proved to be very difficult to obtain data on the actual amount, type, and composition of pesticides used in the various provinces. New Brunswick is the only province which requires distributors to report this information on an annual basis (Shanks, 1983). The only other data available on province-wide use are the surveys conducted in Nova Scotia and Prince Edward Island by the Environmental Protection Service, Atlantic Region, Environment Canada. The report for Prince Edward

Island is available, whereas the report for Nova Scotia is still confidential. Total pesticide use in New Brunswick was about one million kilograms of active ingredients in 1983, including the amount of pesticide used in forest spraying. Prince Edward Island uses about 49,000 kg of active ingredients in its agriculture industry.

Until recently it was thought that pesticides do not form a potential source of groundwater contamination, because of their low solubility, stability, biodegradability, volatility, sorption, etc. However, recent analysis of groundwater in the shallow subsurface in various parts of the country (New Brunswick; Prince Edward Island; St.Laurence Lowlands, Quebec; southern Ontario; Osoyoos area, British Columbia) have shown the presence of pesticides. Pesticides with a relatively high solubility (greater than 30 mg/L) applied to soils with a low water adsorption capacity and a low organic content in areas with relatively large amounts of precipitation (greater than 25 cm/year) could become a source of groundwater contamination. Sandy soils with a low organic content and shallow water-table are prime candidates. This type of soil is present in all provinces. Therefore, although no data are available for the Prairies, it is likely that pesticides. because they are used extensively, may be found in the subsurface also in that part of the country, especially in irrigated areas.

Thus far only areas with the above-mentioned soil type have been investigated. No extensive research has been conducted in areas where soils developed on clayey sediments. It has always been assumed that, because downward movement of liquid is retarded by very low intergranular permeability of these sediments, there is enough time for break-down of the pesticides.

However, as was pointed out earlier, many of these sediments have secondary permeabilities (fractures, desiccation cracks, etc.) which are orders of magnitude larger than their intergranular permeability. It is therefore quite possible that pesticides have migrated downward also in these sediments.

Saline soils have developed during this century in many parts of the dryland farming areas of western Canada. It is estimated that about 2.5 million hectares of arable land in Alberta and Saskatchewan have thus far been lost to this process. In addition, another 100,000 hectares were lost to the same process in irrigation areas in southern Alberta.

Saline soils develop when the water balance of local groundwater flow systems is upset (Fig. 18). The flow systems have been in existence for a long time without causing any significant saline soil development prior to settlement, because the mixture of native plant species was such that it regulated the water balance (Van der Pluym et al., 1981). Destruction of the native vegetation cover, in combination with crop-fallow rotation practices instituted for moisture preservation for grain growing, is primarily responsible for the development of saline soils. During fallow years, water-tables rise due to lack of consumption by plants, and as a result more head is available for movement. This in turn results in the movement of greater volumes of water from the recharge to the discharge area. Along its path in the shallow subsurface, the groundwater dissolves soluble salts and the net effect is an increase in the total amount of dissolved salt transported to the discharge area. Evaporation and evapotranspiration in the discharge area increases the salt concentration in the soil. Where water supply aquifers are present along the flow path of the groundwater, significant increases in the total dissolved solids concentration, up to an order of magnitude, have been found (Van der

Pluym et al., 1981). In many places, the water quality has deteriorated to such an extent that it is toxic to animals, let alone humans.

Saline seep areas can be reduced by limiting the amount of water available for recharge. This can be achieved by changing cropping patterns and/or using high water-consuming plant species. To reclaim the salinized soils, subsurface drainage will have to be installed and appropriate chemical amendments added to the affected area for soil restoration. The mineralized water collected by the drains has to be stored in ponds. After dilution by spring runoff it can be used for irrigation, or discharge to the surface water system during high flow periods only. This will of course cause an increase in the total dissolved solids load of rivers, which in turn may lead to a gradual change in the water quality for downstream users, especially if reservoirs are present.

In areas under irrigation, saline soils can be reclaimed in the same manner. The discharge water from the drains can be returned to the irrigation canals, where it will be diluted and can be re-used, or it can be collected by a separate drain system and either stored or run directly into a stream or river. Whatever method is used, removal of soluble salts from one area will inevitably result in an increase in the salt load in another part of the environment. The long-term implications for downstream use should therefore be considered prior to the initiation of any of the above-mentioned schemes.

4.7 Acid Precipitation

Acid loading of the surface results from both dry and wet deposition. Dry deposition refers to adsorption of particulate and gaseous material on land and water surfaces, whereas wet deposition includes all contaminants reaching the earth's surface in precipitation. Although acid precipitation is not a direct cause of groundwater contamination, the long-term input into the terrestrial environment can lead to changes that are detrimental to the quality of groundwater. Acid precipitation occurs in all areas of Canada. It is concentrated in certain areas in the Maritimes, central Canada, and Alberta, due to industrial activity and/or atmospheric circulation patterns.

Acid loading of the surface can be rendered relatively harmless by neutralization in the soil-rock-water system. However, when the neutralization capacity of the system has been exhausted, a lowering of the pH will occur, which in turn will result in recharge of acidic water to the groundwater flow system. The prime neutralizing agent is calcium carbonate (limestone) and dissolved calcium carbonate and calcium bicarbonate. A number of other neutralization mechanisms exist which involve weathering of silicates and dissolution of metals (Last et al., 1980).

Groundwater recharge areas will be the first to show the effect from acid loading. The continuous downward movement of "acidic" water will deplete the neutralization capacity of the soil, sediment, and rock profile to ever greater depths. On the other hand, discharge areas with their continuous outflow of buffered groundwater will have a much greater neutralization

capacity and are therefore less affected by acid loading. Similarly, basic groundwater discharging into surface water bodies contributes to the neutralization of the acid input into the surface water (Bottomley et al., 1984). The beneficial effects of groundwater discharge will continue until the groundwater itself has become acidic. Once this condition has been reached, surface water bodies will deteriorate rapidly, because the surface water body receives direct input not only from acid loading but also from acidic groundwater discharge. This will have disastrous consequences for local ecosystems. The rate at which acidification of surface and groundwater will proceed depends on the neutralization capacity of the hydrogeological environment. In general terms, the areas most sensitive to acid loading are the Canadian Shield, portions of the Maritimes, and a small part of central Alberta.

A recent review of acid neutralization processes within soil-rock-water systems (Weyer, 1984) indicates that the increase in acidity can result in changes in the permeability of the soil, accelerated downward transport of nutrients, dissolution of heavy metals, changes in the soil biological communities, etc. With time, acid precipitation will cause a reduction in the fertility of the soil, an increase in the heavy metal content of the groundwater, and deterioration of the quality of surface waters.

Up until 1982 a total of at least 1660 scientific articles were published on various aspects of acid precipitation (Wiltshire & Evans, 1984). Judging by the number of papers dealing directly with groundwater (nine) it appears that the effect on the quality of groundwater has thus far not received enough attention.

In Canada, major studies on the effect of acid loading and on the neutralization capacity of the soil-rock-water system are being initiated. As part of the Long Range Transport of Acidic Pollutants (LRTAP) program of Environment Canada, the National Hydrology Research Institute has started a research program to improve the understanding of the physical and chemical processes which neutralize acid loading of the soil-rock-water system, with the ultimate goal to determine the acid neutralization capacity of the system in catchment basins (Weyer, 1984). The fieldwork for this study will be conducted in the Turkey Lakes Watershed in Ontario, which is located on the Canadian Shield. Another major study that has a groundwater component will be undertaken in Alberta. This study will be conducted by the Kananaskis Research Centre of the University of Calgary, and is jointly funded by the oil industry and the provincial government. The primary aim of this study is to determine the effects of atmospheric emissions resulting from oil and gas activity.

At present there is no data base in Canada which can be used to assess the impact of acid loading on the quality of the groundwater in the various parts of the country. Tens of years of monitoring well-defined hydrogeological environments will be required to obtain the necessary data.

V. THE ROLE OF GOVERNMENT IN GROUNDWATER CONTAMINATION

The protection of groundwater resources has, until about fifteen years ago, received a relatively low priority from most governments in Canada. In part this is due to the diffuse distribution of its users (primarily the rural population), and for another part it is due to a lack of appreciation of the significance of groundwater as a resource, its interaction with surface water, the inevitable time delay in contaminant movement inherent to groundwater flow, and the lack of understanding by the general public of groundwater flow. However, an increasing number of cases of groundwater contamination, the very high cost and low success rate of clean-up, and a greater general awareness by the general public of environmental issues have led to the realization that this resource needs as much, if not more, protection than other parts of the environment. This has resulted in new regulations for the protection of groundwater resources.

Groundwater, and thus also its protection, falls under provincial jurisdiction. The federal government has direct authority over navigable waters, interprovincial waters, oceans (within limits), Arctic waters, and unorganized northern waters in the Territories; through fisheries, it also has authority over the quality of water as related to fish life, shipping, energy development, and pest-control products. It has indirect authority over provincial waters where critical conditions require federal assistance (Canada Water Act) and over contaminants when health is being impaired. Jurisdictional problems between the federal and provincial governments are likely to arise where contaminated groundwater discharges into surface water

under federal jurisdiction. In order to protect or maintain the quality of surface water the federal government should know the quality of discharging groundwater. This means that the interactive groundwater-surface water system has to be defined in terms of both quantity and quality. However, under the present division of jurisdictional powers, the maintenance of groundwater quality is the responsibility of provincial governments, and the federal government has to rely on the cooperation of these governments to ensure that the quality and quantity of groundwater discharging into waters under its jurisdiction is maintained.

All provinces have installed networks of observation wells to monitor groundwater levels, but only in Saskatchewan and Alberta has there been a program to also monitor the long-term quality of groundwater in the major aquifer systems in a systematic way. Major inorganic ions and trace metals are being determined. In all other provinces, thus far, groundwater quality monitoring has been site specific, e.g. town water supplies or areas with localized contamination; or chemical compound specific, for example the pesticide aldicarb (New Brunswick, Nova Scotia, and Prince Edward Island). Alberta at present is the only province which is planning the installation of a network of observation wells in the major aquifers specifically designed for the long-term monitoring of organic compounds. Alberta is also planning to determine the age of the water in the major aquifer systems in order to establish the time interval for sampling and the spatial distribution of sampling points with respect to source inputs.

From the foregoing it is obvious that groundwater quality is still poorly defined in most of Canada, and that baseline data on the quality and

changes in quality of groundwater discharging to the major surface water systems are essentially lacking. It appears, therefore, that in order for the federal government to manage the environmental quality of the surface waters under its jurisdiction, it should institute programs in cooperation with the provinces to obtain the necessary data on both the quantity and quality of discharging groundwater. Furthermore, to protect the quality of groundwater, the federal government would have to strengthen the existing legislation concerning substances toxic to health, and regulate the complete cycle of production, transportation, use, and disposal.

Under present environmental regulations and policies enacted by both levels of government, waste disposal to the terrestrial environment should no longer cause groundwater contamination. However, regulations are no good unless they are properly enforced. Unlike American environmental legislation, which is relatively specific and detailed, Canadian environmental laws are more general and their enforcement depends in many instances on the discretion of government officials. It is therefore conceivable that a polluter can continue to contaminate at will until he is stopped by someone prepared to take action. For example, according to an article in the "Calgary Herald" (January 23, 1985), federal government agencies and crown corporations were responsible for 33 percent of about 700 fuel and chemical spills that occurred across the Northwest Territories in the last decade. Of all the spill incidents caused by government agencies and industry combined, less than one percent were taken to court under the numerous environmental laws and regulations. In Prince Edward Island, where almost all water used is groundwater and where the protection of this resource is vital, several

federal government buildings have had fuel tanks installed that are not corrosion-resistant. This is contrary to the federal government's own Environmental Protection Service Guidelines, which require such installation for all federal facilities. These examples illustrate that there is a need to strengthen environmental laws and remove discretion from enforcement.

Another aspect of the environmental protection of the quality of groundwater resources which has to be addressed is the "reasonable use" concept in groundwater management, suggested by the Ministry of the Environment in Ontario (MOE, 1984b). Under this concept the minister decides what constitutes "reasonable use" and potential use of groundwater in the case of land associated with or adjacent to waste disposal sites or contaminant spills. This decision will be made on a case-by-case basis, because the wide variation in the quality, quantity, and availability of groundwater makes a fixed-standard approach impractical (MOE, 1984b). The decision as to the "reasonable use" at a particular location shall be based on:

- the present use of groundwater,
- its potential use, and
- the amount and quality of groundwater that is available.

In most instances the present use will be taken as the reasonable use. Where there is no current use of groundwater, criteria will be established for the potential use. The determination of potential "reasonable use" of the groundwater will be based on the quantity and quality now present in the vicinity of a planned disposal site and the current use of the resource in the general area. In addition, planning agencies may provide input with respect to potential land use in the vicinity of a planned disposal site, as

this might affect the use of groundwater. Attenuation of contaminants by the subsurface environment is one of the most important design criteria for the disposal facilities. This implies that some contamination of the subsurface and limited movement of contaminants within the boundaries of the property containing the landfill site will be allowed. However, contaminant movement is not necessarily restricted to this property. Contaminants will be allowed to enter adjacent property as long as they do not interfere with the use of the soil and do not contaminate the groundwater to a degree which would impair its use. In the case where the groundwater under the adjacent property is presently of better quality than the Provincial Drinking Water Objectives, a lowering of this quality would be acceptable. On the other hand, in areas where the water quality is poorer than the objectives but nontheless used as a drinking water source, no further decrease in quality will be allowed. However, where good alternate supplies of water are available, either from surface water sources or municipal systems, aquifers containing water of poor quality (i.e. less than water quality objectives) can be designated as contaminant attenuation zones.

A number of comments can be made about this suggested approach to groundwater management.

- The concept of "reasonable use" is concerned only with the present and the immediately foreseeable future, but does not address long-term demographic and economic developments.

- The standards for the protection of the quality of groundwater are discretionary. It is true that a number of guidelines for decision-making are provided, but the status of present and potential use of the groundwater

resource under the land adjacent to a waste disposal facility can readily be changed. This can be done, for example, by providing water of equal or better quality from an alternate source to the present or potential users, or by rezoning the adjacent land for a different land use. In both instances the use status of the groundwater resource is changed to such an extent that quality maintenance is no longer necessary and it can therefore be allowed to deteriorate.

- Aquifers with groundwater of a quality better than the provincial drinking water quality guidelines are allowed to be contaminated to a certain degree. This implies that a little bit of contamination is all right, even though it diminishes the value of the resource. On the other hand, no special effort is made to improve the quality of groundwater in aquifers where it is below that specified in the guidelines, but which is nonetheless used in many areas. In other words: excellent quality does not have to be maintained and poor quality is acceptable as long as it does not deteriorate further.

- Inherent in the "reasonable use" concept is the fact that contamination of the shallow subsurface and/or portions of aquifers is allowed. The degree and extent of the contamination is determined by the attenuation capacity of the subsurface environment. In principle, the contamination should be restricted to the waste disposal property, but transboundary flow onto adjacent properties is permitted if the "reasonable use" is not affected. As was pointed out before, the quality criteria are discretionary and can be readily amended. Groundwater is part of the hydrologic cycle and, as was discussed earlier, it provides a significant contribution to the surface water resources. If surface water resources are to be protected because of their significant economic value as a source of fresh water, it makes little sense to contaminate one of

its main inputs. It can be argued that groundwater contamination in isolated areas does not present a problem for the surface-water resources. However, it appears that there are going to be many isolated contaminated areas, which in all likelyhood will differ with respect to the criteria used to maintain the groundwater quality in their vicinity. The question then arises: how many is too many and when does a little contamination become too much? It is obvious that waste-disposal site selection cannot be done on a case-by-case basis, but that the regional impact on both the groundwater and surface-water resources must be considered. Furthermore, by allowing attenuation of contaminants as a design parameter in waste-disposal site selection, portions of the subsurface are excluded from future use. Although provicions can be made to alleviate unacceptable environmental impacts in the future, it is a well-known fact that clean-up is, at best, only partially successful. Most, if not all, hydrogeologists agree that in order to protect the groundwater resources the best approach is to keep contaminants out in the first place. Attenuation should be considered as a last line of defense and definitely not as a primary design parameter.

In summary, the "reasonable use" concept of groundwater management is unreasonable, because it allows contamination of the shallow subsurface and does not offer sufficient protection of the groundwater resources for the future.

If groundwater resources are considered a vital source of fresh water for the present and the future, then industrial development, urban growth, use of agricultural chemicals, density of livestock, disposal of waste, etc., will have to be planned and controlled to maintain and protect the quality of that water.

In order to be able to properly plan land use, the quality and quantity of groundwater resources in any given area as well as the hydrogeological environment must be well defined. The aquifer area can then be zoned according to the sensitivity to contamination, and regulations developed which control the use, transporation, distribution, storage, and disposal of potential contaminants. This means a significant intrusion by senior government in municipal and private affairs and will undoubtedly be seen by local governments and individuals as a curtailment of the economic viability of industrial and agricultural activity in the areas affected by the regulations. However, control of the surface activities in land-use is not a new idea. It is being practiced extensively and successfully in all countries in Europe which rely heavily on groundwater as a fresh water source. The Environmental Protection Agency in the United States is proposing a similar approach to protect many of the groundwater resources in that country (EPA, 1983).

According to guidelines developed by EPA (1984), the groundwater resources are divided into three classes.

Class I. These are groundwater resources particularly vulnerable to contamination because of their hydrogeological characteristics. They are either an irreplaceable source of drinking water for a substantial population, or they provide water for a sensitive ecological system. Hazardous waste facilities will be banned as well as leachable pesticides. Existing waste facilities will be strictly regulated and any contamination will have to be cleaned up to background levels or standards for drinking water.

Class II. These are groundwater resources that are current or potential sources of drinking water or have other beneficial uses. They comprise the

vast majority of groundwater. The level of protection received by these resources will be in accordance with existing EPA regulations. In areas where the groundwater is vulnerable to contamination and is currently used for drinking water, new hazardous waste facilities will be banned and current contaminating facilities will have to clean up to drinking water quality or background levels. Where contamination can be contained by plume management and protection of human health and the environment can be demonstrated, the stringent clean-up requirements may be waived.

Class III. These are groundwater resources that, because of natural or man-made contamination levels, are not considered potential sources of drinking water and have limited beneficial use. The protection of these resources will be less stringent. However, technology standards for hazardous waste facilities would be the same as for the other classes. If contamination does occur, a waiver could be granted to clean up to a less stringent concentration limit for contaminants since the groundwater is already of limited value. However, such waivers would not be available to facilities causing contamination that precludes future use of the groundwater.

Although the EPA could legally draft legislation for all of the United States under the Clean Water Act, the Safe Drinking Water Act, and a number of other laws pertaining to water, at present it is encouraging the states to draft their own legislation, the rationale being that an overarching approach to the problem would not work because geology, hydrogeology, and possible sources of contamination differ widely among states.

A similar variation of conditions exists in Canada. Because of the diversity in land-use and in its effects on the economic base in the various provinces,

and because of the differences in the sources of water used by the various economic sectors in each province, the level of protection awarded to the groundwater resources and the enforcement of the regulations varies widely among provinces. As has been mentioned in several places in this report, groundwater and surface water form part of an interactive system. In addition, a significant portion of the surface-water resources represents continuous discharge of groundwater, especially in winter. Protection of the groundwater resources is therefore paramount not only in those areas which rely on this resource, but equally important in those areas which use primarily surface water. In order to protect the quality of the surface water resources for future use in Canada, the federal government should assume a much more active role. Although it is realized that groundwater is a provincial resource, the protection of this resource is in the national interest, and should as such be defined in a policy of the federal government. The operational aspects of such a policy could be left to the provincial governments and tailored to their own unique economic and hydrogeological environments. This approach would be similar to that used in the United States. The overriding role of the federal government would guarantee a uniform approach to the protection of the groundwater resources in Canada.

The province of Quebec appears to be moving rapidly in the direction of land-use control. Municipalities have been organized into regional districts for the purpose of land-use planning. One of the parameters considered is the sensitivity to contamination of the groundwater resources for a particular use of land. Maps identifying groundwater contamination-potential have been prepared for a number of areas, for example the Mirabel region (Simard, 1977).

Recently, pesticides were found in the groundwater in a number of areas. To avoid large-scale problems, the Quebec government plans to determine the sensitivity of agricultural lands to downward migration of pesticides. Once this information has been collected, a licensing system for their use will be initiated.

The control and regulation of pesticides , as well as their impact on the environment and human health, fall under federal jurisdiction. The responsibility for control is generally shared with the provinces. Whereas surface waters have been monitored routinely for pesticides over the last decade, groundwater surveys have only recently begun. Most of this work was done in eastern Canada. The results of these surveys indicate that pesticides are present in the groundwater in a number of places. Since the federal government is the primary agency in the control of pesticides, it should initiate, in cooperation with the provinces, a monitoring program of the groundwater resources to determine the extent and severity of the contamination, and conduct a cause-and-effect study. The results from this study can then be used in the testing program for certification and to adopt and implement appropriate controls.

A concerted effort should be made by the federal government and the provincial governments to assess the degree of groundwater contamination in the vicinity of abandoned mine sites. In many of the old mining districts long-term monitoring of the surface water environment has shown that the abandoned mine sites have had a considerable deleterious impact on water quality. Although surface input of contaminants can be readily identified, little or nothing is known about the extent and degree of groundwater

contamination, nor is the contribution by groundwater discharge to the total contaminant loading of the surface water resources known. This information will be required in any scheme for the restoration of the quality of surface-water resources, especially if it is considered that it could represent a very significant cost factor in the required remedial work.

One of the main problems encountered during the preparation of this report was a lack of access to specific information on incidence and magnitude of groundwater contamination caused by various types of waste in the provinces. Without a proper data base the assessment of the stress on groundwater resources caused by contamination is speculative at best. In order to properly manage groundwater resources and adopt and implement appropriate controls to protect the resource for continuing use in the future, readily accessible data banks should be available, not only for in-house use but also for outside examination.

VI. CONCLUSIONS AND RECOMMENDATIONS

Demands on water in surface-water systems will increase significantly in the future, especially in western Canada. Additional withdrawals and reservoir construction will alter existing groundwater flow regimes. The cumulative effects will be changes in the downstream surface-water quality, which in many cases will have inter-provincial ramifications. The available data base is in most instances inadequate to assess long-term effects and should be improved by a considerable research and planning effort on the part of the federal government.

The cost-benefit ratio of artificial recharge to supplement existing groundwater supplies as an alternative to surface-water storage schemes for water supply should be more thoroughly evaluated. Artificial recharge significantly reduces losses of water through evaporation, improves the colour and taste of surface water, and provides temperature stabilization. Furthermore, the surface area required for artificial recharge schemes is only a fraction of the area required for equivalent volume storage in surface reservoirs. In addition, artificial recharge can be used to arrest saltwater intrusion in coastal areas, simultaneously increasing the volume of groundwater available for withdrawal.

The incidence, degree, and extent of groundwater contamination across Canada are poorly defined. It is therefore suggested that the federal government, in cooperation with the provinces, initiate a national data bank on groundwater contamination. Not only would such a central registry provide a real time overview of the quantitative and qualitative stresses on Canadian

groundwaters, but it will also aid in identifying common denominators and/or specific contaminants which require changes in existing regulations.

The quality of groundwater resources in Canada is poorly defined. In comparison to surface-water resources, the systematic long-term monitoring of the quality of groundwater is still in its infancy. Little or no information is available on heavy metals in groundwater or organic compounds deleterious to health. The federal government should investigate the possibility of initiating a groundwater quality monitoring program in cooperation with the provinces. This program could run parallel to the surface-water quality sampling program that is conducted and administered by Environment Canada.

In many areas in Canada, leachate from abandoned mines and mine tailings poses a threat to the quality and the biocommunity of the surface water in their vicinity. Little or no information is available on the extent and the degree of groundwater contamination and the contribution to the contaminant load in the surface water due to discharge of contaminated groundwater. This information should be available for the design of the most cost-effective clean-up program. It is suggested that the federal government conduct a number of detailed studies at abandoned mine tailing sites in different hydrogeological and climatic settings to determine the magnitude of the potential contribution of contaminated groundwater to the surface water.

The protection of groundwater resources in Canada varies according to the significance of the resource as a source of drinking water and the availability of alternate surface-water sources. To provide for uniformity in the protection of this resource across Canada, the federal government should assume a more active role and formulate a national groundwater

protection strategy in order to assure the present and future use in the national interest. Because of the similarities in geology, hydrogeology, and land-use between Canada and the United States, the strategy developed by the Environmental Protection Agency in the United States could serve as a model for Canada. Once guidelines and specific requirements have been developed, their implementation could be delegated to the provinces.

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GLOSSARY

ANION. An ion that moves, or would move, toward an anode, hence nearly always synonymous with a negative ion.

AEOLIAN. A term applied to deposits which are formed due to the transporting action of the wind.

ATTENUATE. To reduce in value, quantity, and strength.

CATCHMENT BASIN. Drainage basin.

CATION. An ion that moves, or would move, toward a cathode, hence nearly always synonymous with a positive ion.

CATION EXCHANGE. The property of certain minerals which can sorb certain cations and retain them in an exchangeable state, i.e. these ions are exchangeable for other cations by treatment with such ions in a water solution.

CHELATION. The inactivication of metallic ions in a solution by an organic reagent with whose molecules the metallic ions are strongly bound in a relatively inactive ring structure.

CLASTIC SEDIMENTARY ENVIRONMENT. An environment where detritus is transported mechanically into its place of deposition. The commonest clastics are shale and sandstone.

COLLAPSE STRUCTURES. Structures resulting from the collapse of overlying beds into caverns formed by solutioning.

CONSOLIDATION. A process whereby loose and soft earth materials become firm and coherent.

DECALCIFICATION. The removal of calcium carbonates from the rock mass.

DIAGENETIC CHANGE. The chemical and physical changes that sediments undergo during and after their accumulation.

DIFFUSION. The process whereby ionic or molecular constituents move under the influence of their kinetic activity in the direction of their concentration gradient.

DISPERSION. The spreading of solutes in the subsurface away from their point of entry due to the branching of pore channels,which causes the solute to be diluted.

ESKER. A serpentine ridge of gravel and sand deposited by water under glaciers.

FACIES. The "aspect" belonging to a geological unit of sedimentation, including mineral composition, type of bedding, fossil content, etc. Sedimentary facies are areally segregated parts of differing nature belonging to any genetically related body of sedimetary deposits.

FLUVIAL SEDIMENTS. Sediments deposited by rivers.

GLACIO-FLUVIAL DEPOSITS. Sediments deposited by flowing water in close proximity to glaciers and ice sheets.

HOLOCENE SEDIMENT. Recent sediments, i.e. sediments deposited after those deposited during the Pleistocene epoch.

IDIOMORPHIC (Euhedral). Minerals that are bounded by their own crystal faces.

IGNEOUS ROCK. Rock formed by solidification of hot mobile material termed magma.

INTRUSIVE HISTORY. The sequence of invasions of igneous rock invading older rock.

ION. An electrically charged atom, radical, or molecule, produced by the dissolution of an electrolyte.

ISOTROPIC. A medium is isotropic with respect to permeability if it is equally permeable to flow in all directions.

KAME. A conical hill or short irregular ridge of gravel or sand deposited against the edge of an ice sheet.

LITHOFACIES. The physical character of rock which indicates its mode of origin.

MACROSCOPIC. Visible to the naked eye.

METAMORPHIC ROCK. Rock which has formed in the solid state in response to pronounced changes of temperature, pressure, and chemical environment.

OUTWASH. Stratified drift that is stream built (deposited by meltwater streams) beyond active glacier ice.

PENECONTEMPORANEOUS. A term used to describe a process that took place at almost the same time as the deposition of the material of the surrounding rock.

PERMEABILITY. Capacity for transmitting a fluid.

PIEZOMETER. The basic device for measurement of hydraulic head. It is a tube or pipe in which the elevation of a water level can be determined.

PLEISTOCENE. The earlier of the two epochs comprised in the Quaternary period, also called Glacial epoch and formerly called Ice Age.

PLUTONIC. A general term applied to a class of igneous rocks which have crystallized at great depth and have as a rule assumed a granitoid texture.

SORTED. A term used to indicate the degree of similarity of the component parts in the mass of material.

SUBSIDENCE. Local or regional sinking of the ground.

TECTONIC. Pertaining to, or designating the rock structure and external forms resulting from the deformation of the eath's crust.

TILL. A non-sorted, non-stratified sediment carried or deposited by a glacier.

UNCONSOLIDATED SEDIMENT. A loose and friable sediment.

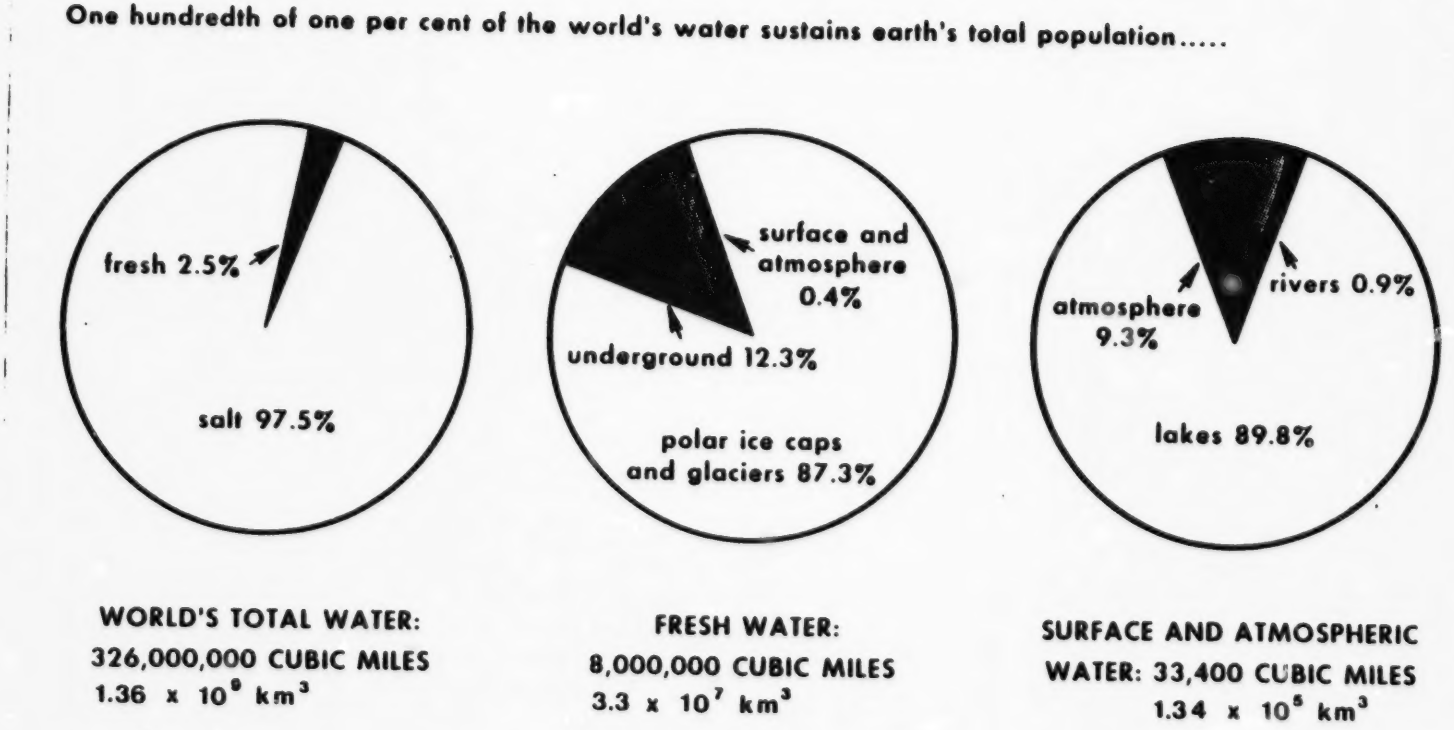


Figure 1. Distribution of water on the earth (after Morris, 1969)

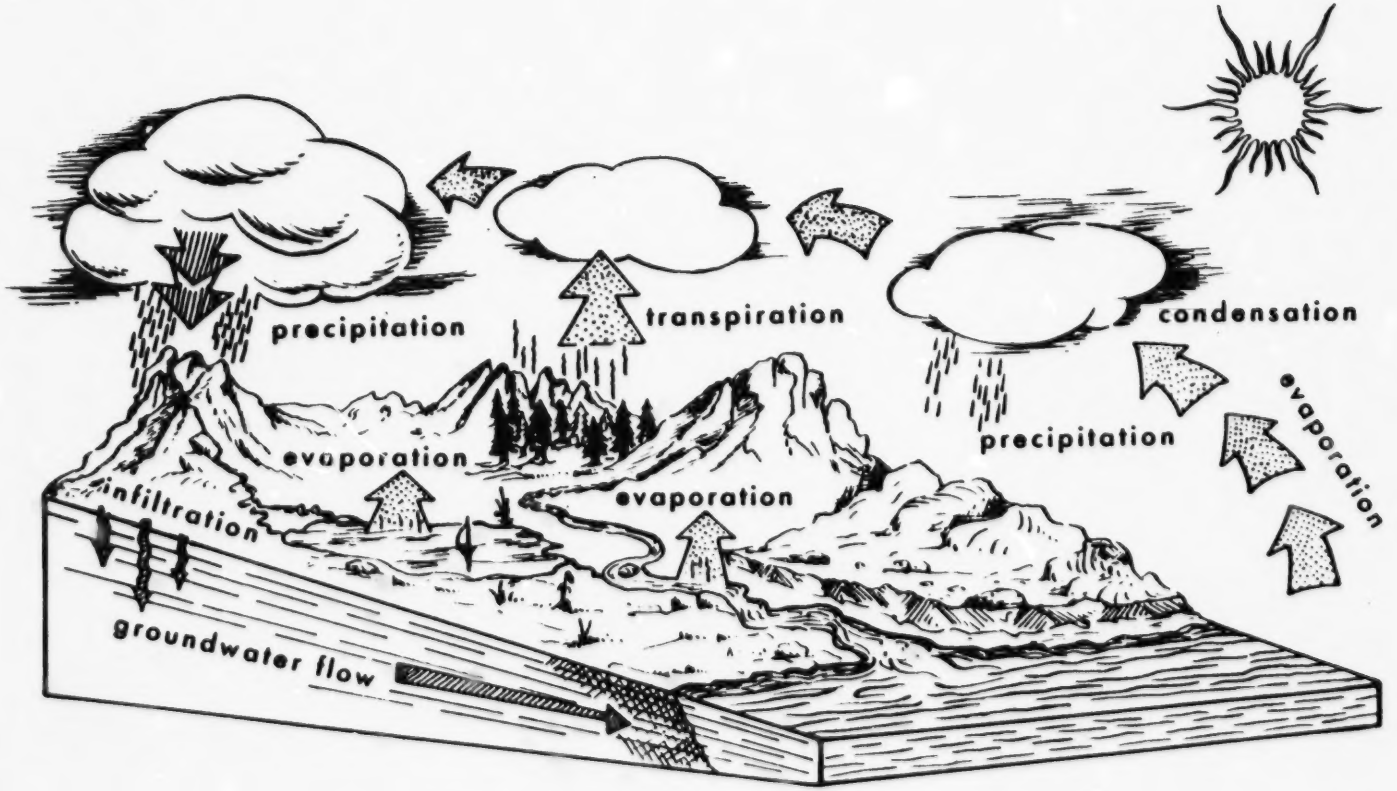


Figure 2. The hydrologic cycle (after Morris, 1969).

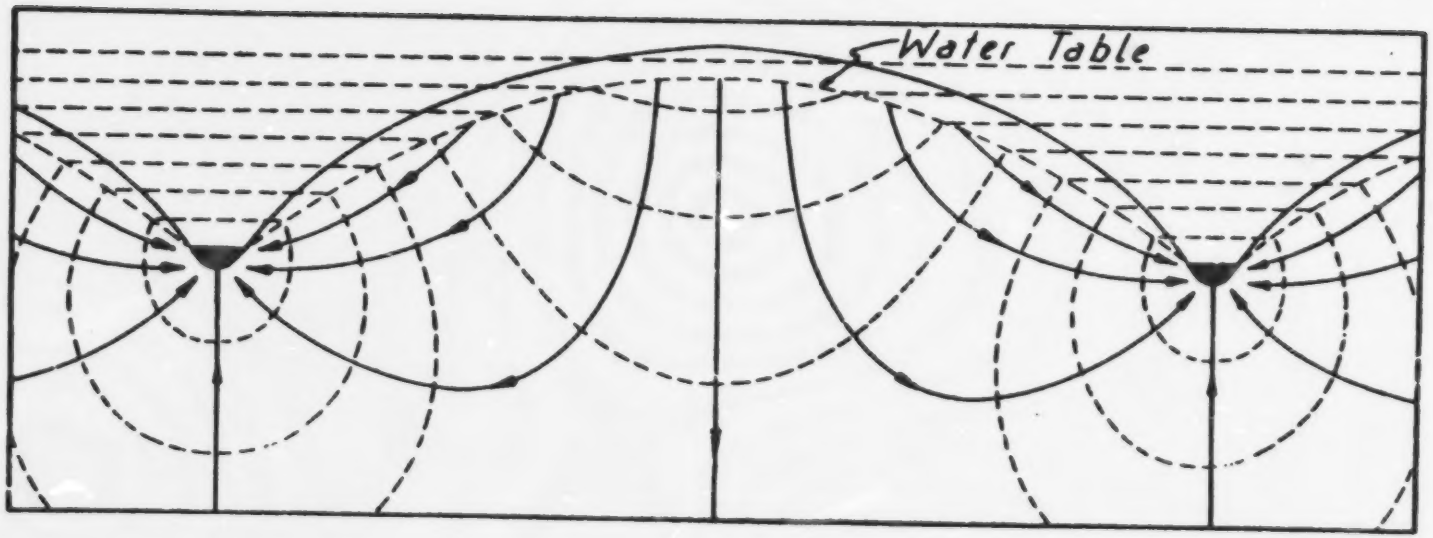


Figure 3. Approximate groundwater flow pattern in uniformly permeable material (after Hubbert, 1940)

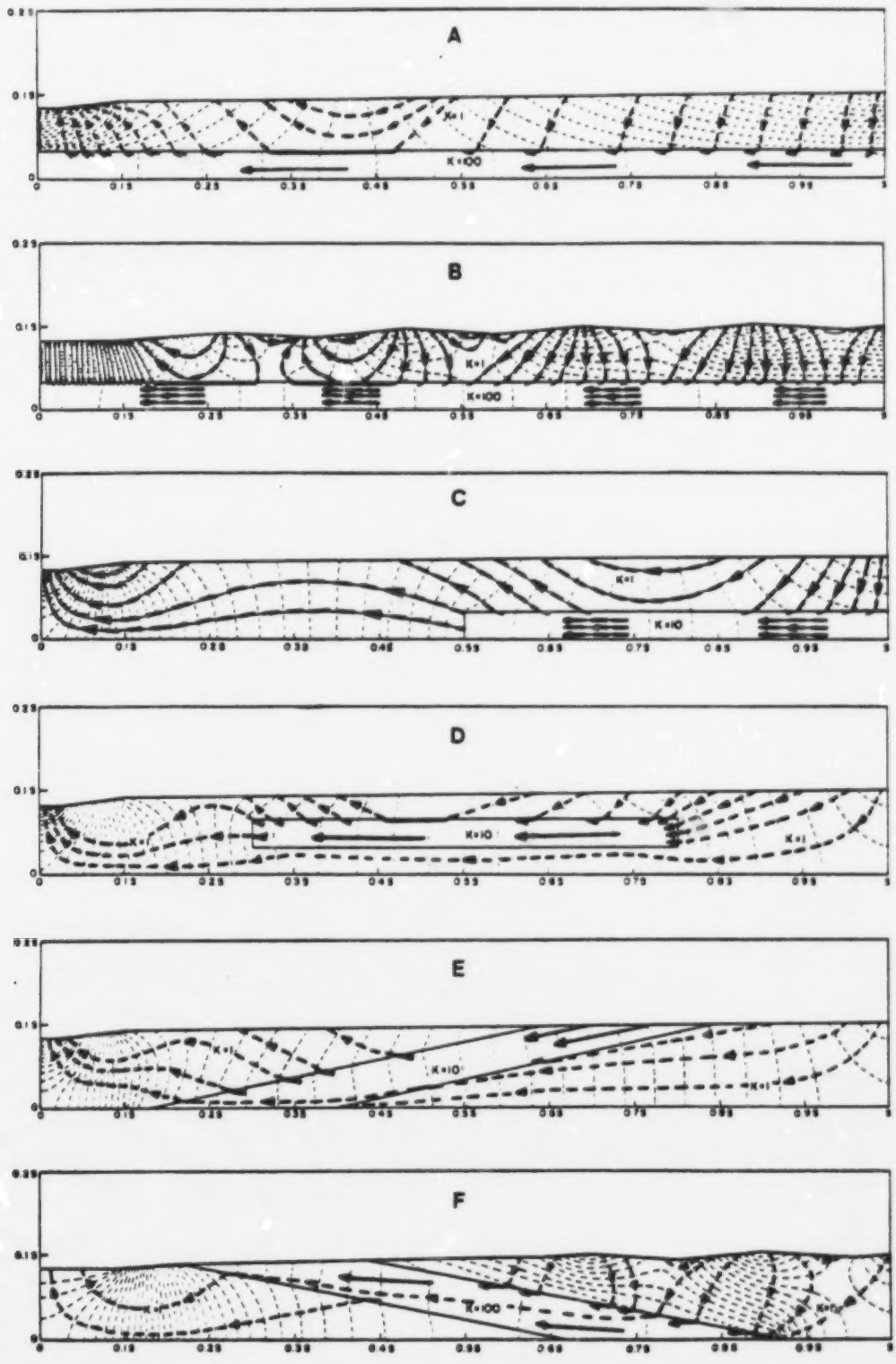


Figure 4 . Effect of topography and geology on regional groundwater flow patterns (after Freeze and Witherspoon, 1967).

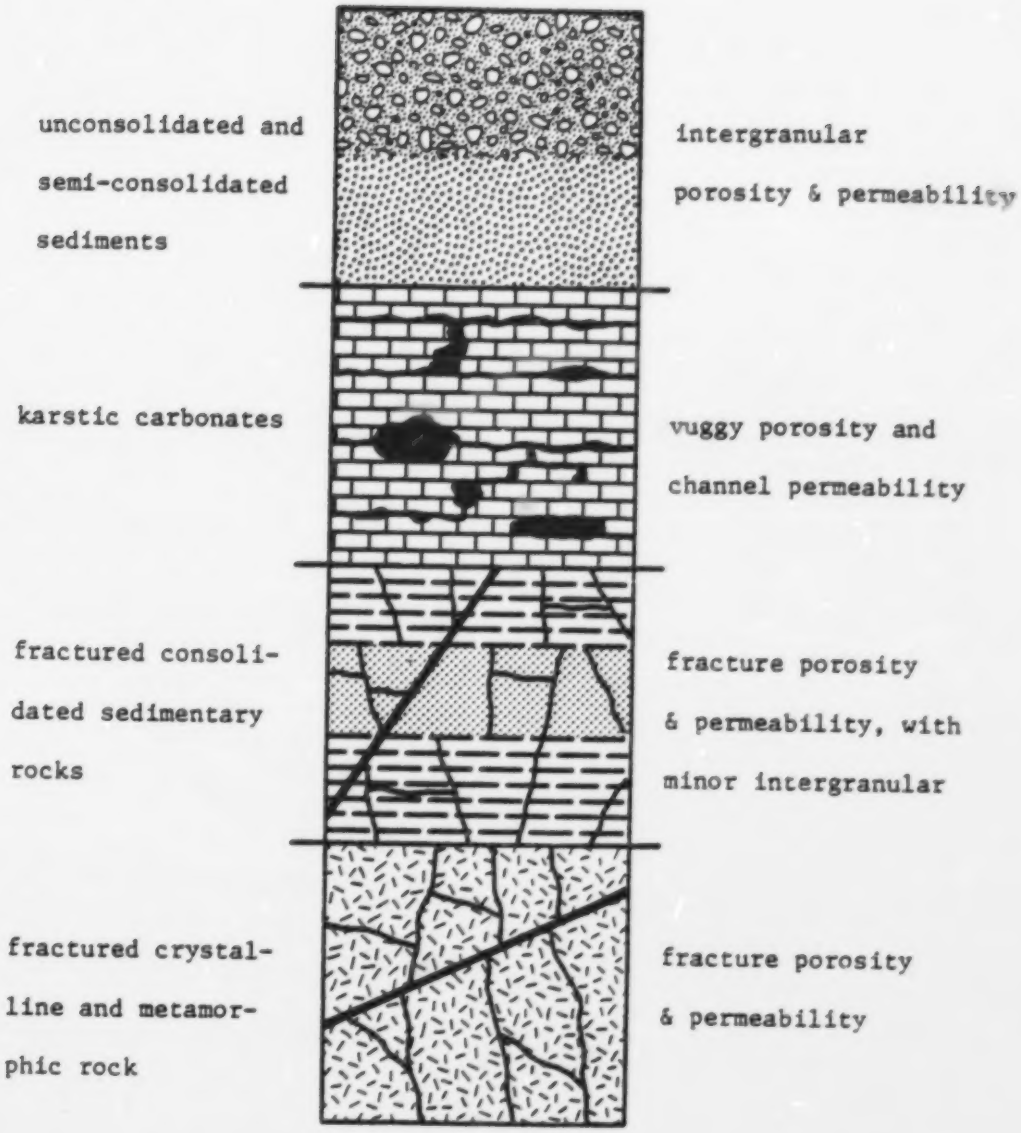


Figure 5. Texture, porosity, and permeability in major rocktypes and deposits.

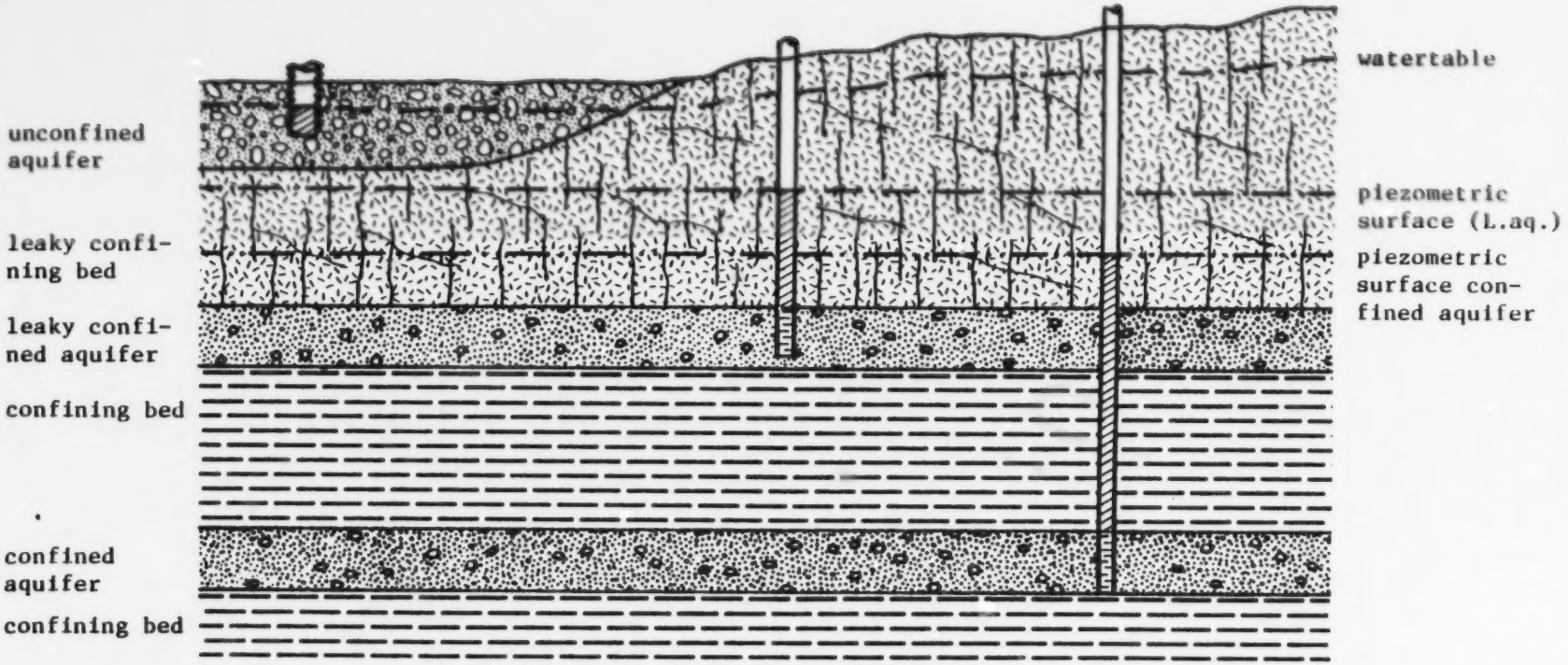


Figure 6. Unconfined, confined, and leaky aquifer.

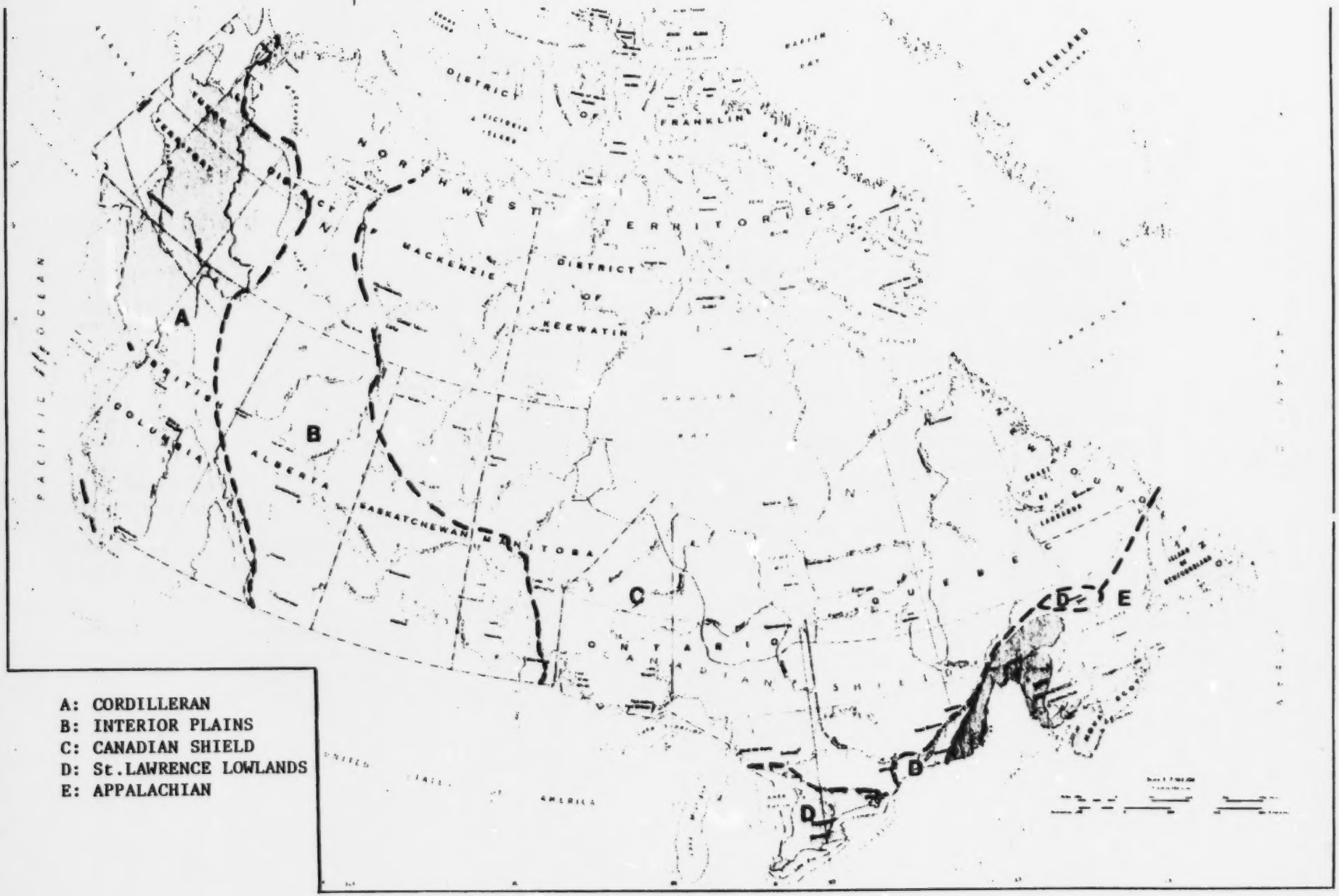


Figure 7. Distribution of main hydrogeological regions of Canada (after Brown, 1967).

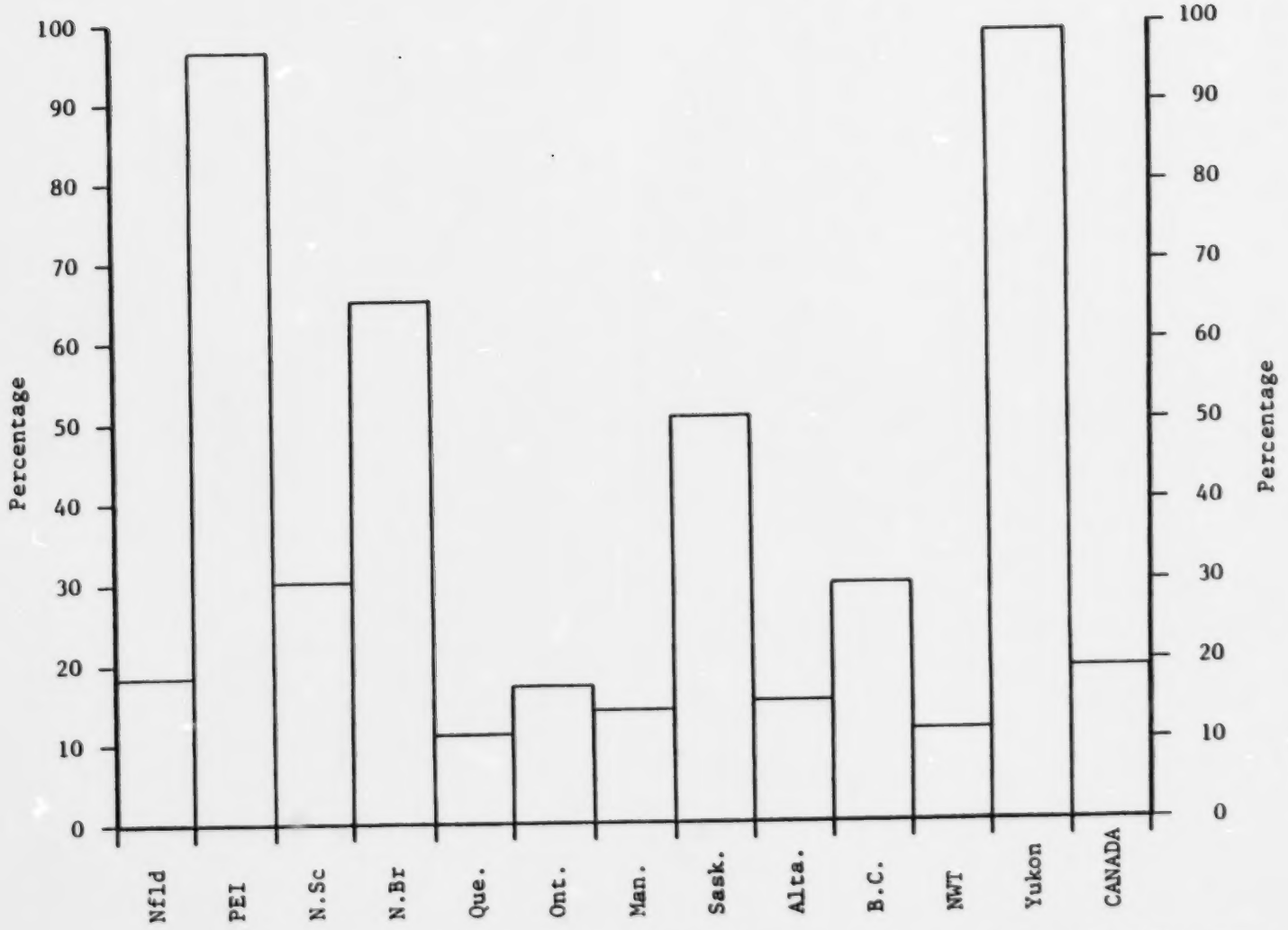


Figure 8. Groundwater component of total water use by population in provinces and Canada (after Hess, 1984).

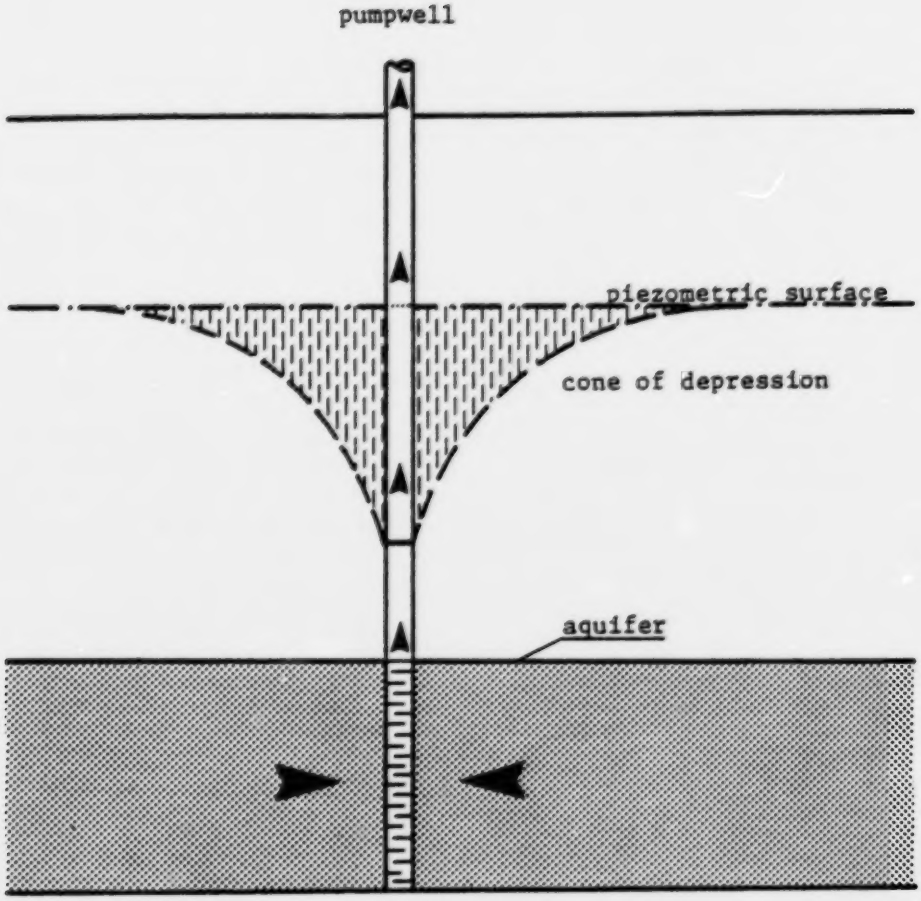
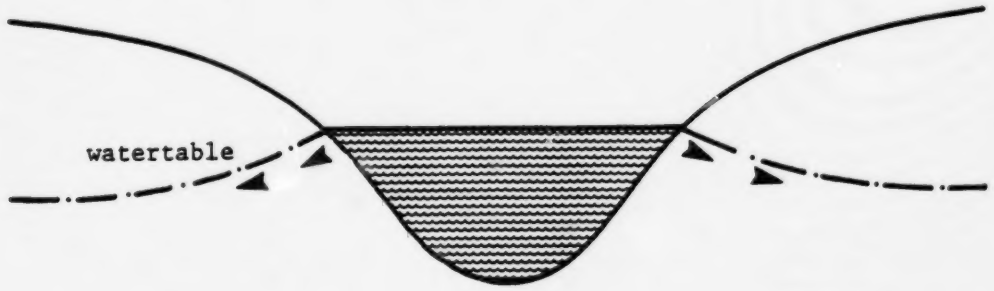
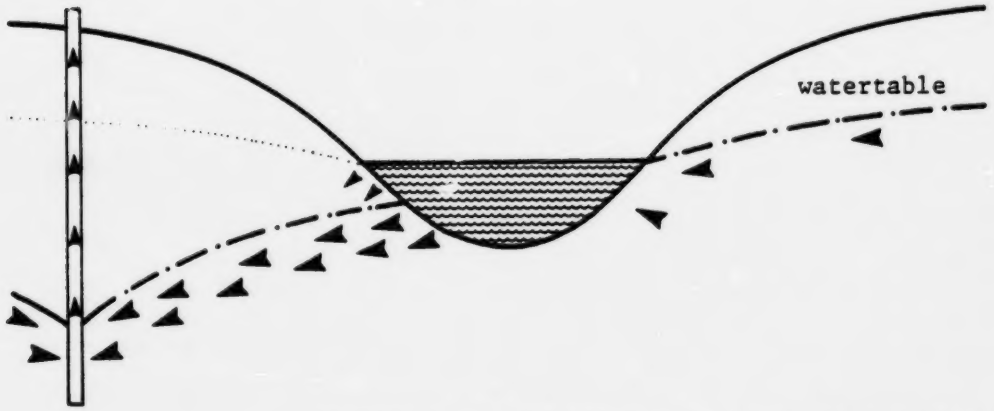


Figure 9. Cone of depression created by pumping.



high river water level: groundwater recharge

low river water level: groundwater discharge



induced infiltration caused by pumping a well

Figure 10. Relationship between groundwater flow and streamflow.

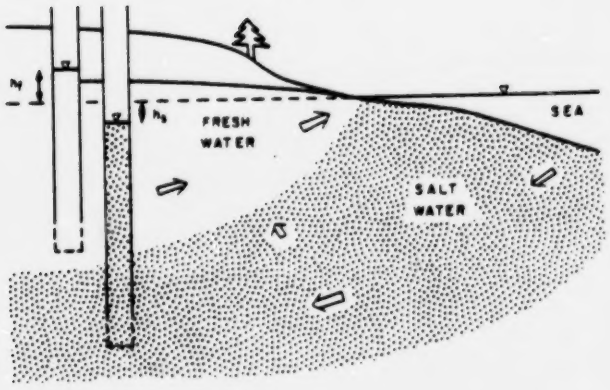


Figure 11. Fresh-salt water contact, head distribution, and flow of fresh and salt water (after Van der Kamp, 1981).

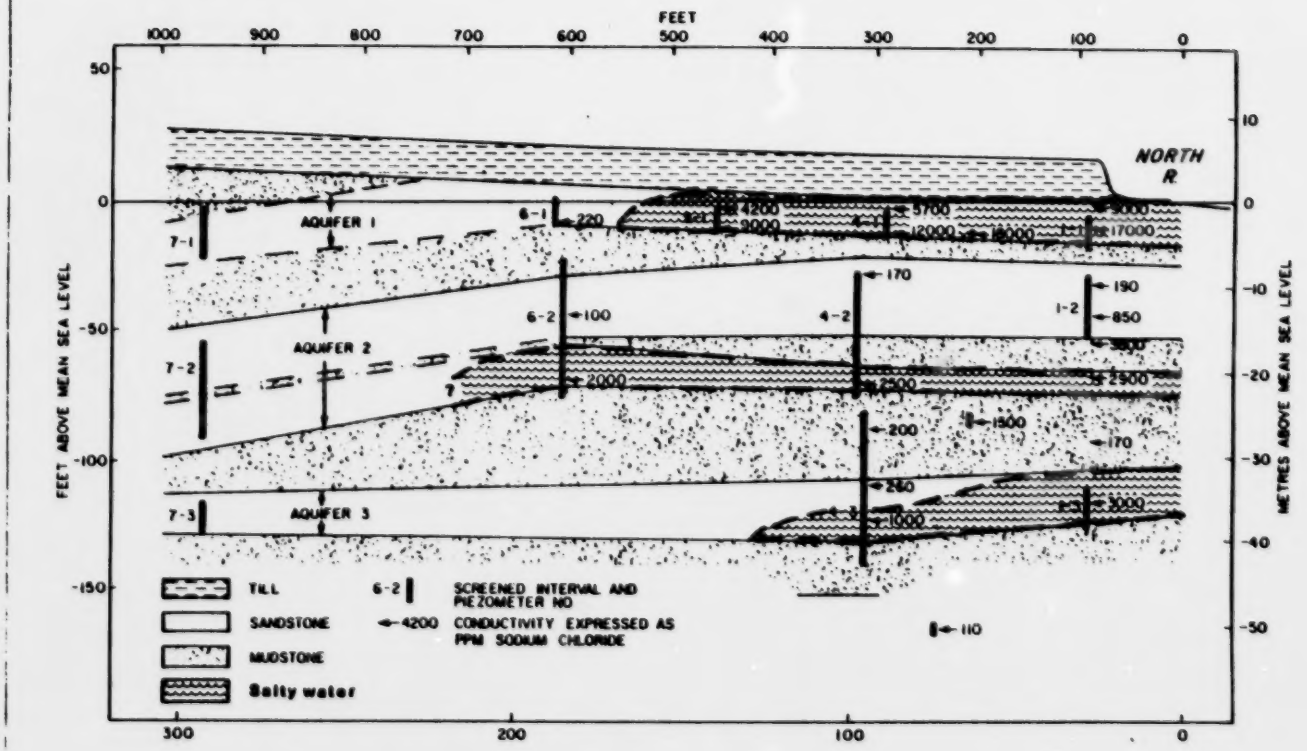
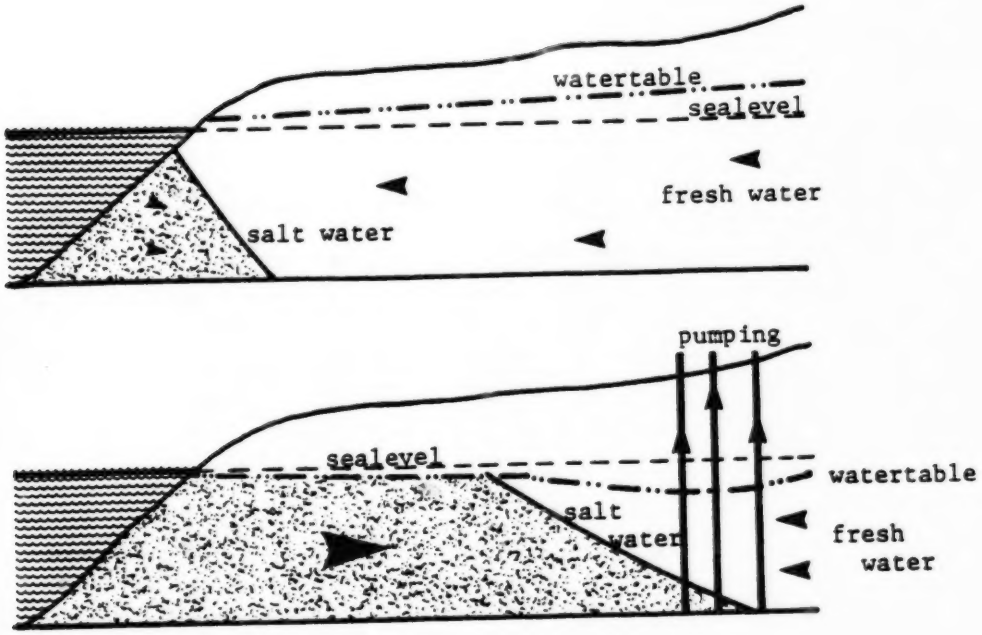
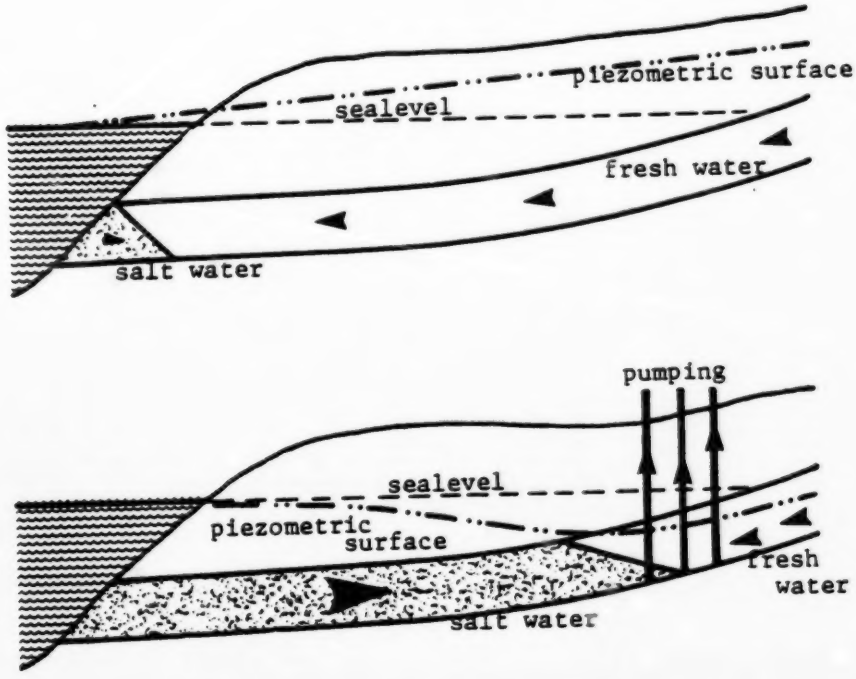


Figure 12. Hydrostratigraphy and salinities encountered during drilling at York Point, Prince Edward Island in 1970 (after Van der Kamp, 1981)

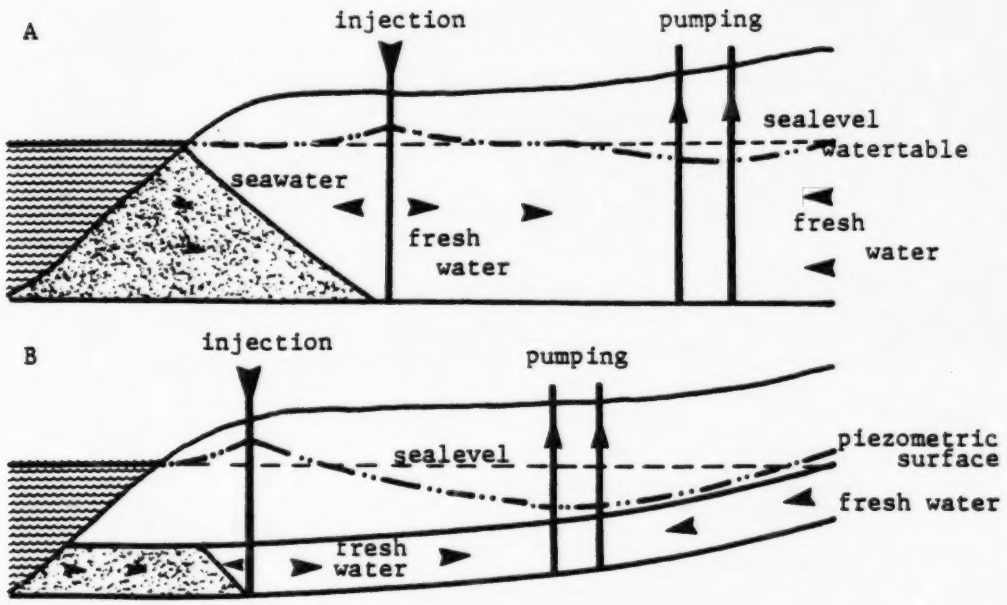


Hydrologic conditions in an unconfined aquifer

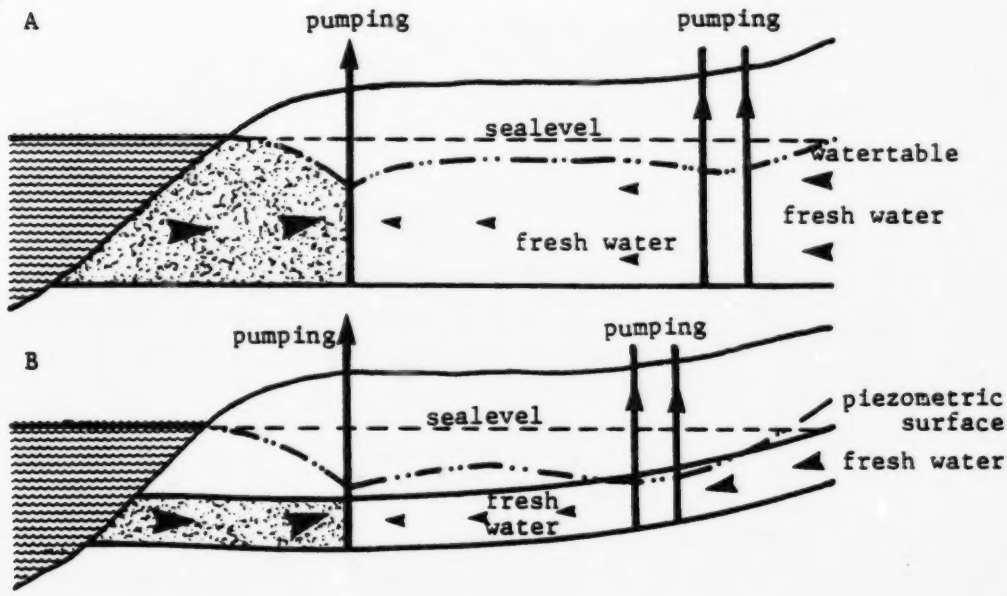


Hydrologic conditions in a confined aquifer

Figure 13. Change in hydrologic conditions due to groundwater extraction in coastal aquifers (after Todd, 1974).



Hydrologic conditions with a fresh water ridge acting as a salt water barrier. A: unconfined B: confined



HYdrologic conditions with an extraction-type sea water barrier
A: unconfined B: confined

Figure 14. Conceptual diagrams of methods employed to control seawater intrusion (after Todd, 1974).

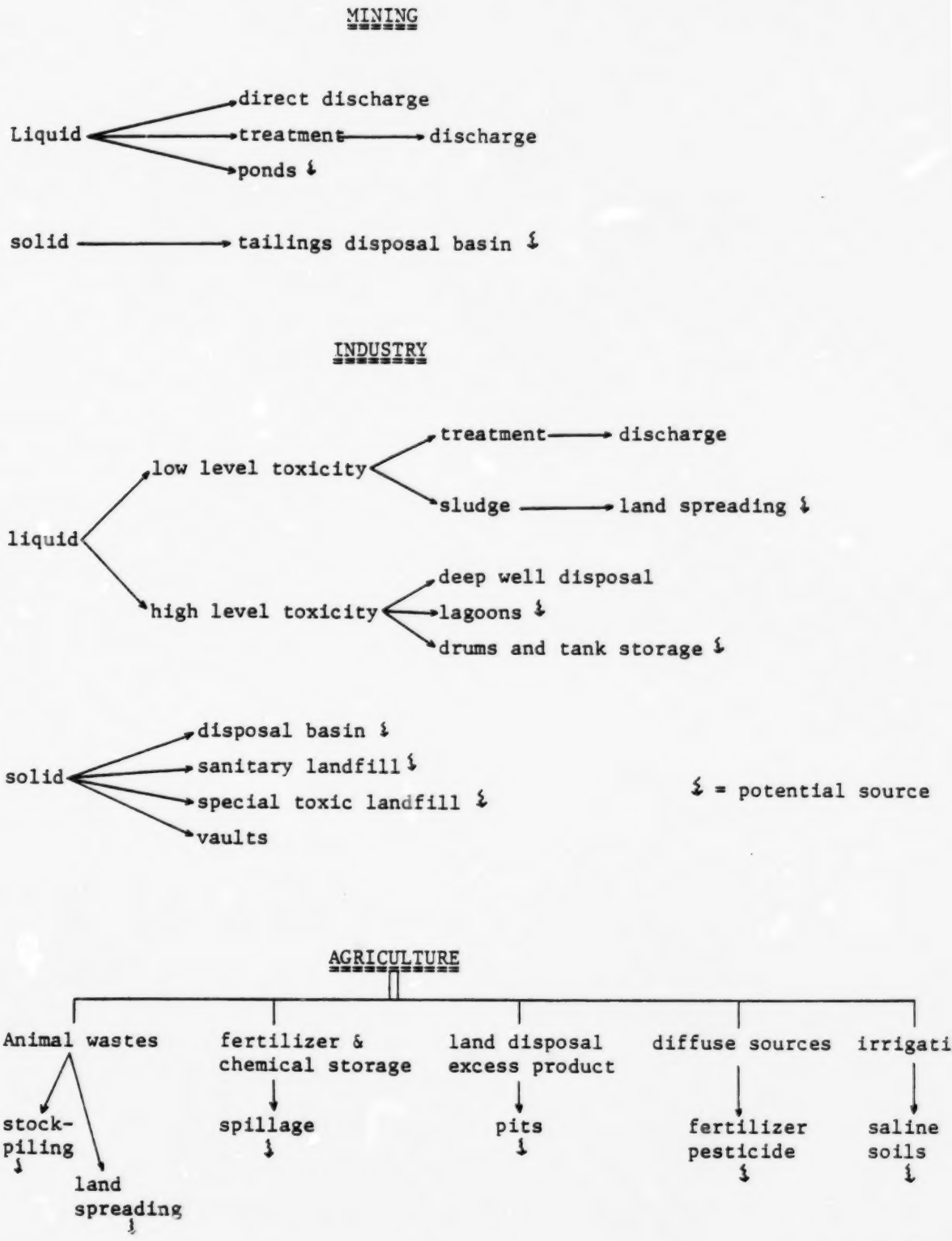


Figure 15. Disposal practices and groundwater contamination

OIL INDUSTRY

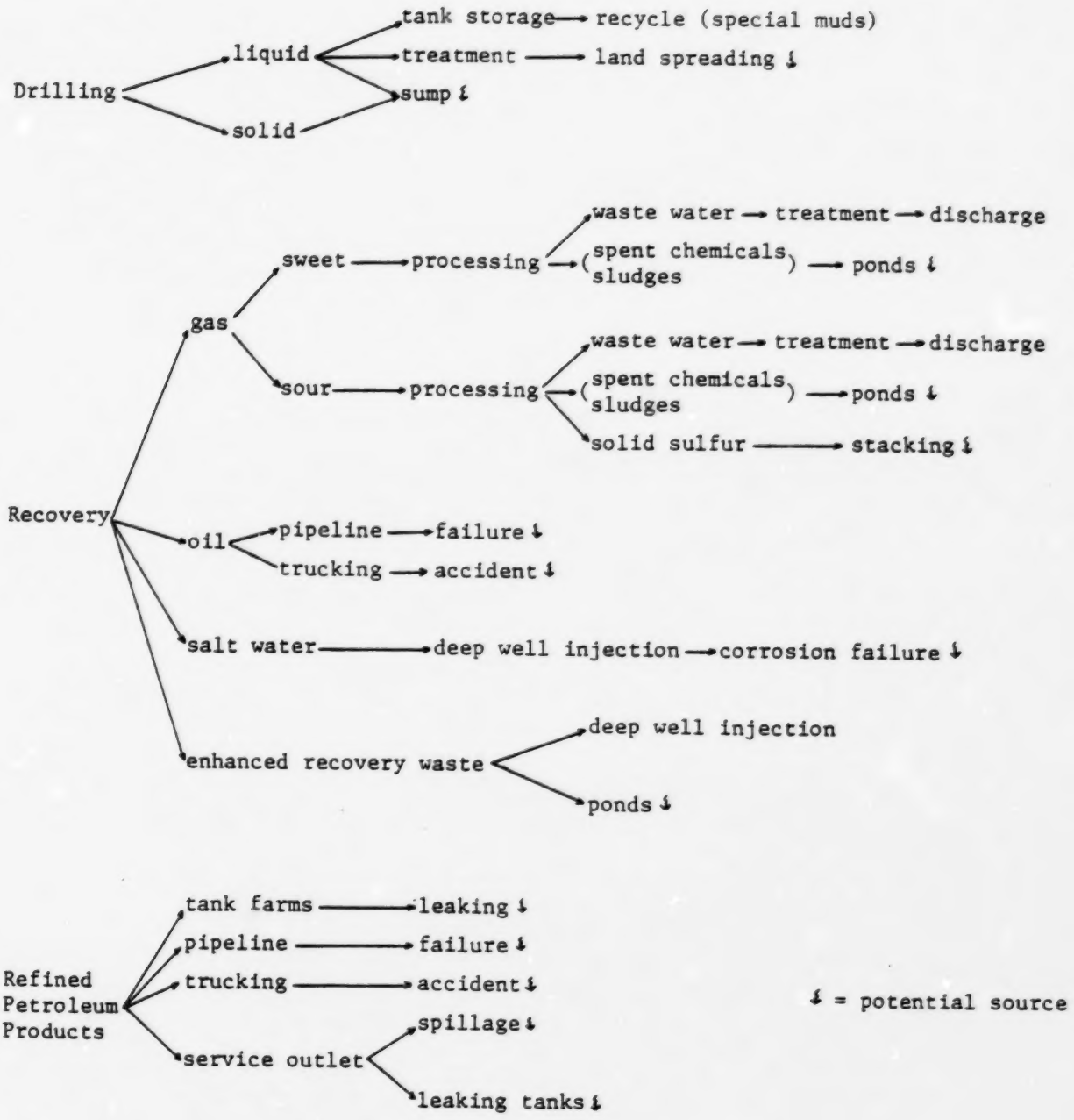


Figure 15. Disposal practices and groundwater contamination (cont.).

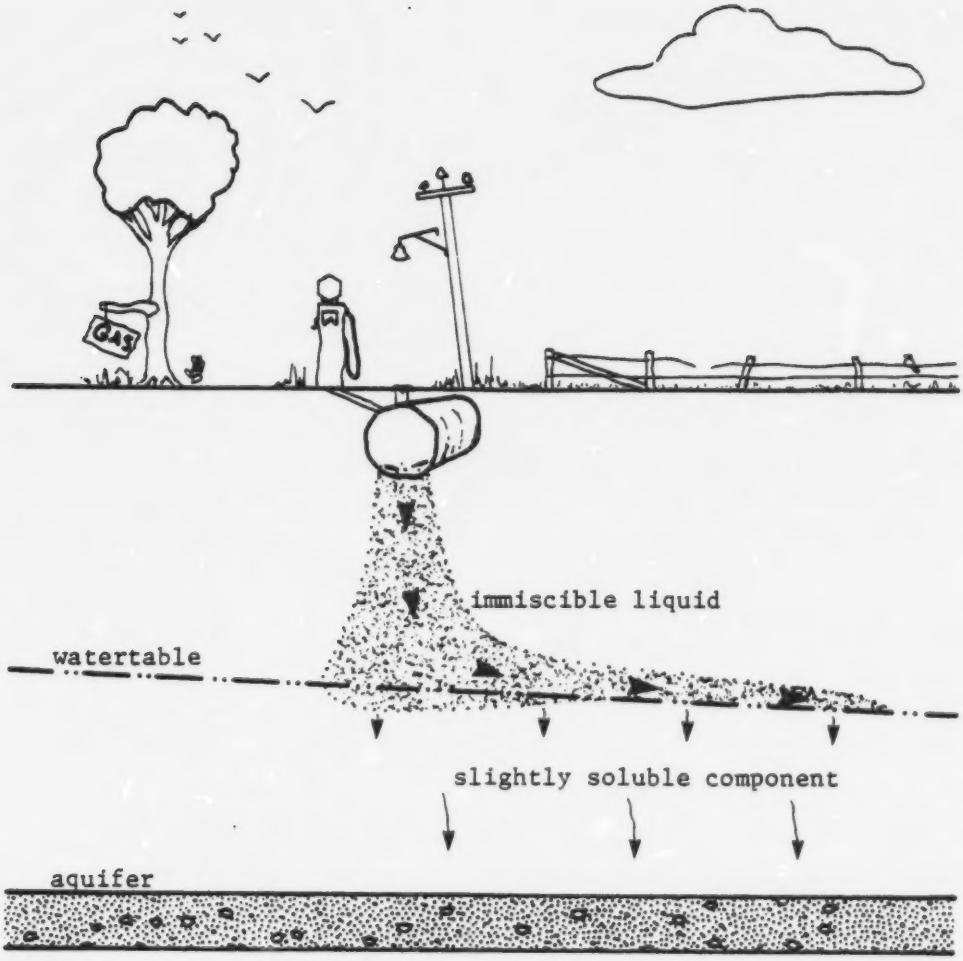


Figure 16. Distribution of immiscible contaminants in shallow subsurface.

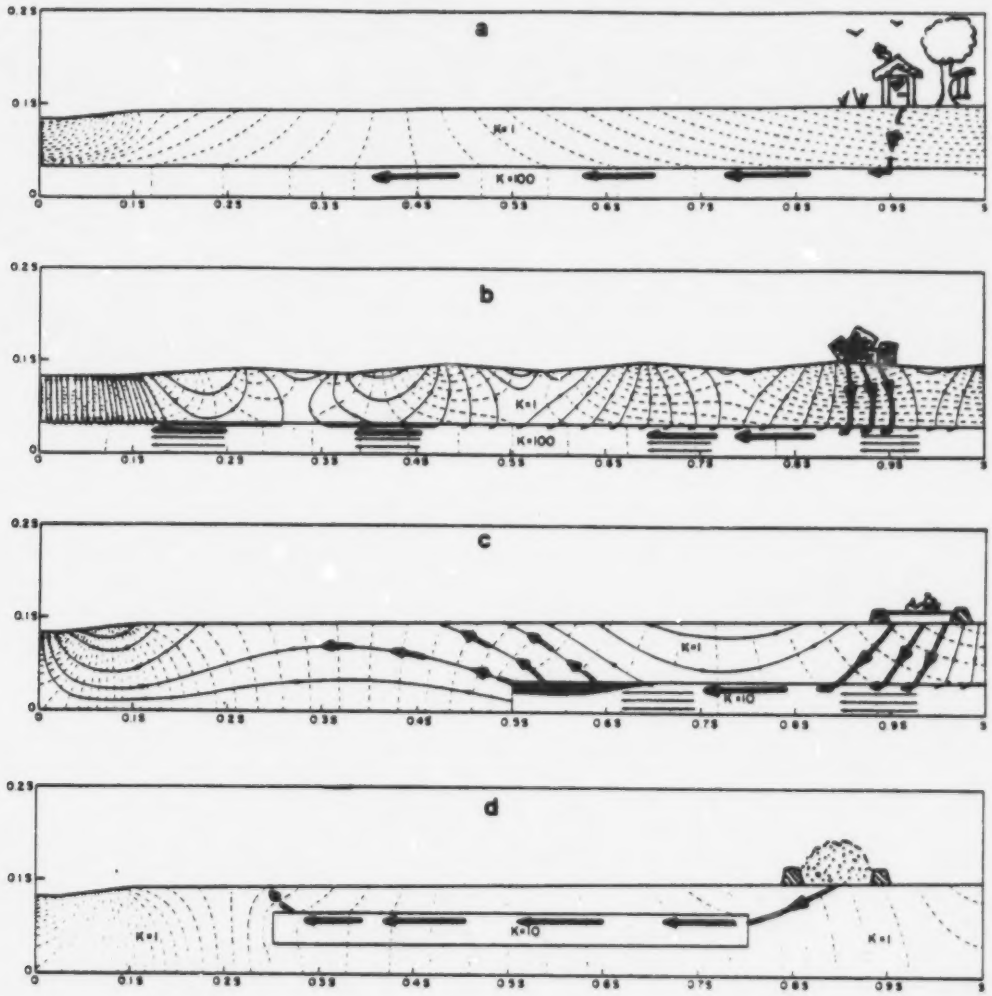


Figure 17. Flow of contaminants in the subsurface.

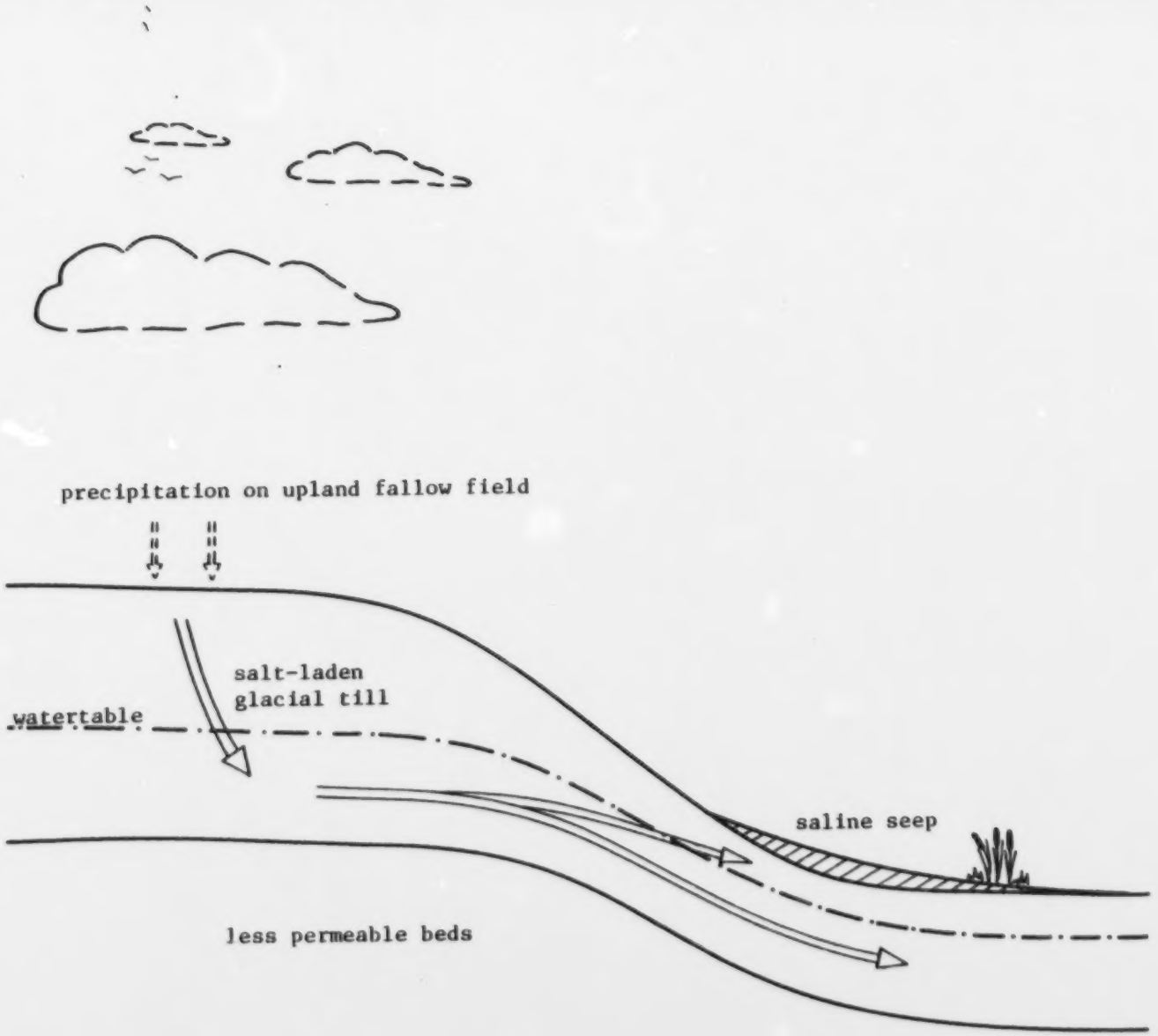


Figure 18. Conceptual diagram of saline seep formation (after Van der Pluym et al., 1981).